NASA CONTRACTOR REPORT 177381

BASD - SIRTF Telescope Instrument Changeout and Cryogen Replenishment (STICCR) Study

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EXECUTIVE SUMMARY

This study addresses the techniques and hardware required to extend the useful life of SIRTF by on-orbit servicing. Most of the work was directed to replenishment of the superfluid helium cryogen, and special emphasis was placed on assessing the impacts of servicing SIRTF at the Space Station. Concepts were also developed for changing the instruments at the focal plane of the SIRTF telescope, and mission operations and timelines were analyzed.

The overall conclusion of the study is that on-orbit cryogen replenishment and instrument changeout is feasible. The modifications to the baseline SIRTF design are not major, and are likely to carry a dewar lifetime penalty of only 7 percent. The operations can be based on either the Shuttle Orbiter or on the Space Station, and the mission timelines are compatible with either location.

Several possible concepts for replenishing the cryogen were examined, and narrowed down to filling the SIRTF from an Airborne Support Equipment (ASE) dewar launched full from the ground within 60 days of the operation. The helium should be transferred in the superfluid state near the SIRTF final operating temperature of 1.8K to obtain the maximum cryogen life in SIRTF after replenishment. For example, transferring the helium in its normal state at between 2.7 and 4.2K would leave between 15 and 40 percent empty volume in the SIRTF dewar after cooling to 1.8K. Two viable pump types are available: thermomechanical pumps (consisting of a porous plug and a heater), and conventional centrifugal mechanical pumps. Because the choice of pump has relatively minor impact on the overall SIRTF and ASE configurations, the two types should be developed in parallel to minimize program risk. Internal analysis effort at Ball Aerospace Systems Division has shown that transfer at 1000 liters per hour is feasible using a thermomechanical pump, and is described in an appendix to this report.

The changes to the baseline SIRTF concept required to accommodate cryogen replenishment consist of plumbing modifications to enhance rapid cooldown. The fill and vent lines must be enlarged from 1.9 to 2.5 cm, and an additional heat exchanger, vent line, and large porous plug phase separator must be added. The additional heat leak introduced decreases the dewar lifetime by about 7 percent.

The ASE required for helium replenishment consists of a large dewar carrying electronics and a transfer line, plus a control console mounted in the Shuttle cabin or Space Station manned logistics module. The dewar is based on the IRAS/COBE technology, and the configuration has been chosen to minimize the length of Orbiter bay used. Concepts for the smallest (5,300 liter) and largest (11,750 liter) sizes potentially required have been developed. A modified version of the Multimission Modular Spacecraft Flight Support System (MMS/FSS) Cradle A is used to support SIRTF when servicing with the Shuttle. The ASE required to service a still-wet SIRTF weighs 2,250 kg, and that required to cool SIRTF from 300K after instrument changeout (the worst case) weighs 4,097 kg.

To make on-orbit changeout of focal plane instruments practical, access must be provided through the back end of the SIRTF telescope dewar. Contamination concerns require that SIRTF be warmed to near 300K before being opened. By using thermal contraction joints in the vapor-cooled shields inside the dewar, a concept for a one-piece swinging door that can be easily operated by an astronaut has been developed. The impact on the instruments is moderate, and consists of placing electrical and thermal strap interfaces at the rear, plus adding handles and smooth outer covers for astronaut safety. The heat sinking function should be performed with demountable flexible straps, and not be combined with the structural support and precise positioning functions.

Detailed operational sequences and timelines have been developed for the various servicing missions based on either the Shuttle or the Space Station. The worst-case timeline is that for instrument changeout on the Shuttle; the

6.2 days estimated fits within the 7-day nominal Shuttle mission, and allows for contingencies and normal crew rest scheduling. The principal safety concern centers around damage to the astronauts' suits by contact with cold surfaces or leaking cryogen. The principal operational uncertainty centers around possible contamination of the SIRTF instruments by particulates or water vapor emitted by the suits. A stand-alone summary of servicing SIRTF at the Space Station is provided as an appendix.

Section 1
REPORT OVERVIEW AND SUMMARY OF RESULTS

This report presents the findings of the SIRTF Instrument Changeout and Cryogen Replenishment (STICCR) Study performed for NASA-Ames Research Center (ARC) by Ball Aerospace Systems Division (BASD) under Contract Number NAS2-11979. This section of the report summarizes the study results. The succeeding sections present our analysis in detail; backup data and additional information are contained in the appendices.

The Space Infrared Telescope Facility (SIRTF) is a long-life space-based telescope for infrared astronomy from 2 μm to 700 μm currently under investigation by NASA-ARC,[1] and planned for launch in approximately 1995. Table 1-1 summarizes its overall characteristics, and Figure 1-1 shows what it might look like.

SIRTF will operate as a multi-user facility, initially carrying 3 instruments at the focal plane. It will be cooled to below 2 K by superfluid liquid helium to achieve radiometric sensitivity limited only by the statistical fluctuations in the natural infrared background radiation over most of its spectral range. The lifetime of the mission will be limited by the lifetime of the liquid helium supply, and is currently baselined to be 2 years.

In order to maximize the scientific return for the total overall cost of the SIRTF mission, it will be necessary to periodically replenish the liquid helium cryogen to extend the life to 10 years or more. It would also be highly desirable to be able to replace the instruments in order to recover from the failure of an instrument, to upgrade them to take advantages of advances in the technology during the mission lifetime, or to adjust the capabilities of the facility to better serve the evolving priorities of the

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1 "SIRTF, Free Flyer Phase A System Concept Description," NASA-Ames Research Center, Moffett Field, CA, PD-1006 (May 3, 1984).

Table 1-1

CHARACTERISTICS OF THE BASELINE SIRTF

PARAMETER	BASELINE
TELESCOPE TYPE	CASSEGRAIN, 85 CM APERTURE
WAVELENGTH COVERAGE	1.8 - 700 μM
OVERALL LENGTH	8.8 M
OVERALL MASS (FULL)	7250 KG
ORBIT	900 KM, 28°
CRYOGENIC SYSTEM	
BASELINE	4000 LITERS SUPERFLUID HELIUM
ALTERNATE	3280 LITERS SUPERFLUID HELIUM
	1650 LITERS SOLID HYDROGEN
LIFETIME (NOT REPLENISHED)	2 YEARS

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HARDWARE EVOLVES TO NASA FREE FLYER SIRTF IN PHASE III

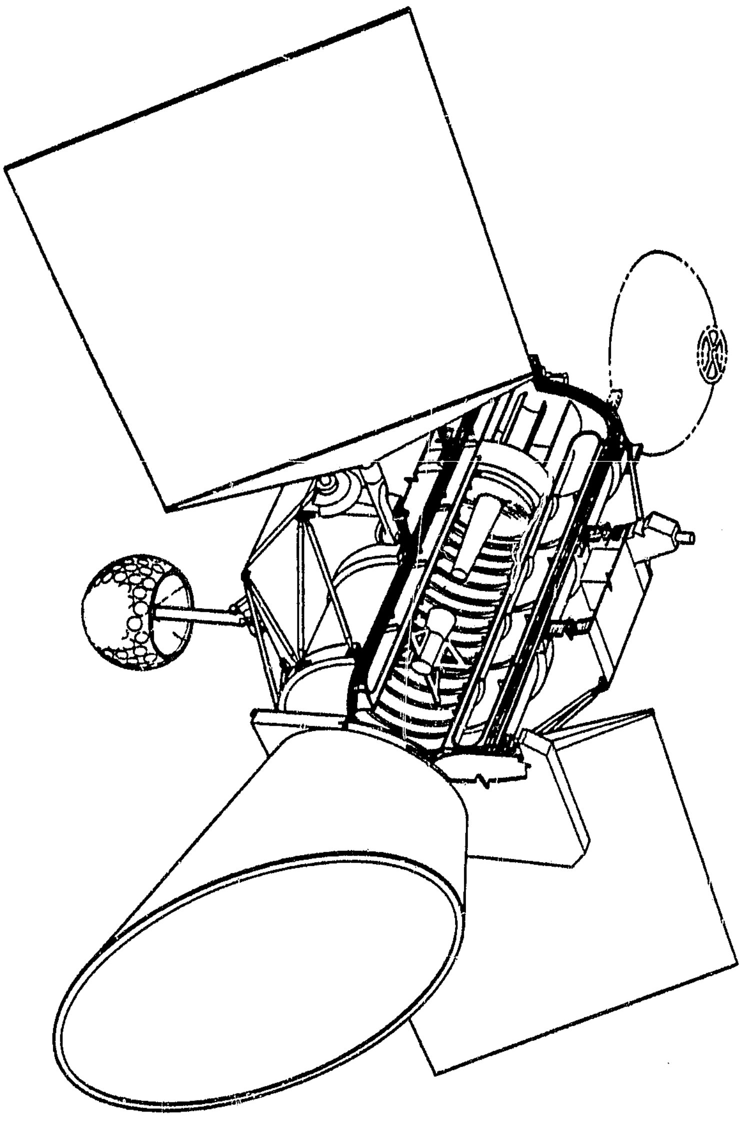

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Figure 1-1 SIRTF as a Free Flyer

scientific community. In addition, certain mission-critical mechanisms located in the helium dewar, such as cryogen valves, the beam-switching mirror, or the oscillating secondary mirror of the telescope, may need to be serviced to achieve the full mission life.

Scope of the STICCR Study

The principal tasks set out by the study Statement of Work, as augmented during the study, were to:

- Define concepts for replenishing the SIRTF cryogen, and for the required Airborne Support Equipment (ASE) required;
- Define concepts for changing out the focal plane instruments, and for servicing other cold mechanisms;
- Analyze the mission implications of servicing SIRTF, based either on the Space Shuttle or on the Space Station;
- Evaluate the impact on Space Station; and
- Develop a plan for demonstrating the required technology.

The bulk of the effort was to be directed toward cryogen replenishment, and special emphasis was to be placed on analyzing the impacts of a SIRTF servicing mission on the Space Station.

Study Approach

We set for ourselves two principal goals: (1) to address the issues of cryogen replenishment and instrument changeout with enough breadth to address all of the realistic options; and (2) to perform the analysis in

enough depth to give insight into the overall feasibility of the operations, and to assess their impacts on the rest of the mission. The resulting conclusions will be useful in guiding overall SIRTF planning decisions, even though much more detailed work must be done before hardware tradeoffs can be completed.

The approach that we have used starts with decision trees that list the operation or design options. These trees are designed to organize the options in a way that makes it easy to see if any reasonable ones have been overlooked, and to guide us in performing analysis and tradeoffs at the highest possible level.

The results attainable with the study resources available has been greatly extended by work done on other studies or programs. Much of the cryogenic analysis has utilized a 35 node thermal model of SIRTF developed on the Thermal and Cryogenic Study for SIRTF performed earlier for NASA-ARC by BASD. Realism of the analysis has been enhanced by experience and test data obtained by BASD on the IRAS program, and by test data currently being obtained in the completion of the COBE dewar.

The work currently under way at the National Bureau of Standards (NBS) in conjunction with NASA-ARC on the development of centrifugal pumps has enabled us to direct more attention to an alternate technique based on the peculiar properties of superfluid helium. The Cryogenic Fluid Management Facility (CFMF) work sponsored by Lewis Research Center (LeRC) has greatly simplified analyzing the impact of servicing a SIRTF which uses solid hydrogen as an auxiliary cryogen.

This study has also benefited from internally-sponsored theoretical and experimental investigation of the critical element servicing SIRTF: the transfer of superfluid helium at high flow rates in zero gravity. The insight gained is summarized in the body of the report, and an appendix gives some recent results of detailed simulation studies.

1.1 CRYOGEN REPLENISHMENT

The cryogen replenishment effort addresses the techniques to be used in transferring superfluid helium into SIRTF in space, the modifications to the baseline SIRTF design that would be required, and the design of the special Airborne Support Equipment (ASE) that would be used. In addition, we explore the replenishment of a dual-cryogen system that also uses solid hydrogen, and of a smaller helium-3 subsystem used to produce temperatures below 1 K in the SIRTF focal plane instruments.

1.1.1 System-Level Tradeoffs

Two basic choices precede the development of the hardware and operations needed for cryogen replenishment:

- The basic replenishment scenario, and
- The physical techniques used to transfer the superfluid helium.

We address these before going on to define the ASE hardware and operations.

Mission Concept Options

Figure 1-2 shows that the first decision is whether to fill SIRTF directly from a tank filled on the ground, or to fill it from a permanently orbiting cryogen storage facility. Given the baseline assumption of this study that the servicing of SIRTF is the specific driving requirement, establishing a permanent storage facility cannot be justified. SIRTF is expected to require replenishment only every 2 years or more, implying that any permanent storage unit would have to be refilled before each SIRTF replenishment. Exploratory analysis also shows that the amount of helium consumed in cooling down the permanent storage tanks would more than double the volume of cryogen launched from the ground, adding to the cost of the resupply tankage.

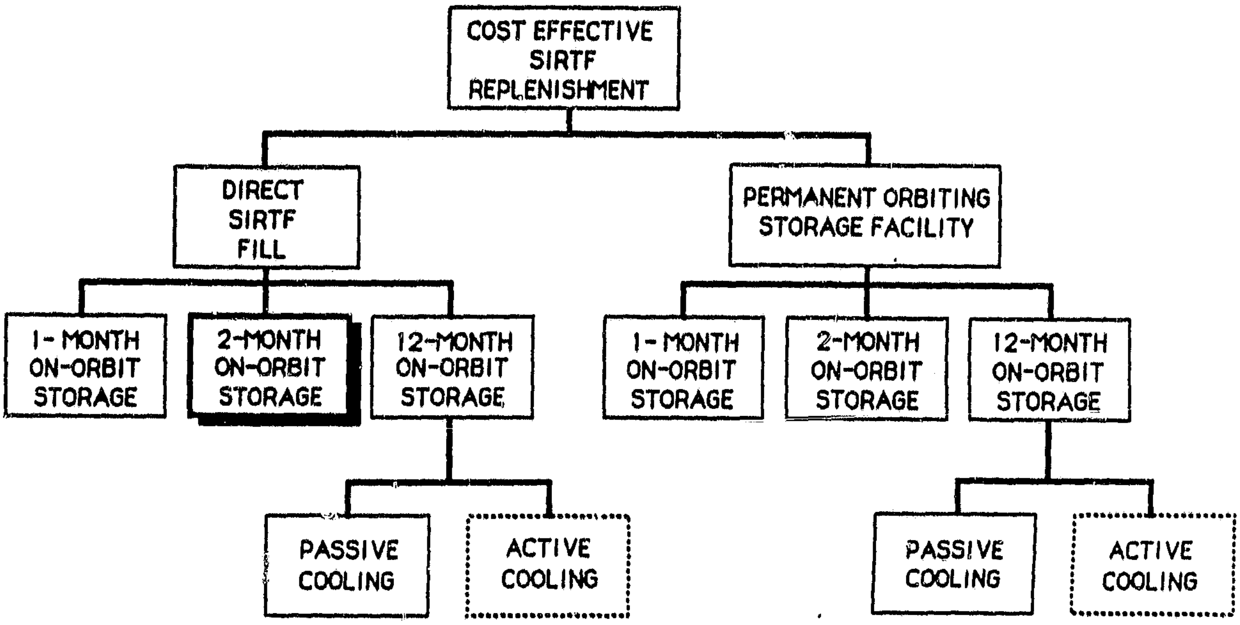

Figure 1-2 Replenishment Mission Options

For purposes of this study, we have therefore chosen to fill SIRTF directly from the resupply tank launched from the ground, and treat the replenishment of other payloads as secondary in our analysis.

The second basic choice to be made is the on-orbit storage time for which the ASE should be designed. The boiloff rate of a passive dewar based on the IRAS/COBE technology is low enough that the volume penalty of designing for 2 months instead of 1 month is only 4 percent, with even lower mass and cost penalties. The non-linear dependence of parasitic heat leak on volume, however, means that extending the on-orbit hold time to 12 months would require either doubling the volume, or adding active refrigeration, with substantial complexity, reliability, and cost penalties. Since it is likely that 2 months is adequate to allow for launch scheduling and orbit transfer windows, we have designed for a 2-month storage (plus 1 month of margin) before filling SIRTF.

Replenishment Technique Options

The choice of the liquid helium transfer technique is guided by the decision tree shown in Figure 1-3. First, we have chosen to transfer He II (superfluid helium, below 2.18 K) into SIRTF, rather than transfer He I (normal liquid helium) and then cool it to convert to He II. Second, we have chosen to use either a thermomechanical pump or a conventional centrifugal mechanical pump to move the liquid from the ASE to SIRTF.

The choice of He II as the state in which to transfer the cryogen is driven by the impact on the cost of the ASE and the cryogenic lifetime of SIRTF after replenishment, and is supported by the knowledge that at least one, and probably two, viable techniques exist for propelling the He II liquid. Figure 1-4 shows that when He I is cooled from a temperature above 2.18 K to the final SIRTF operating temperature of about 1.8 K, liquid is lost due to evaporative cooling. The empty volume in the SIRTF dewar after conversion represents additional lifetime that could be realized if it were filled at

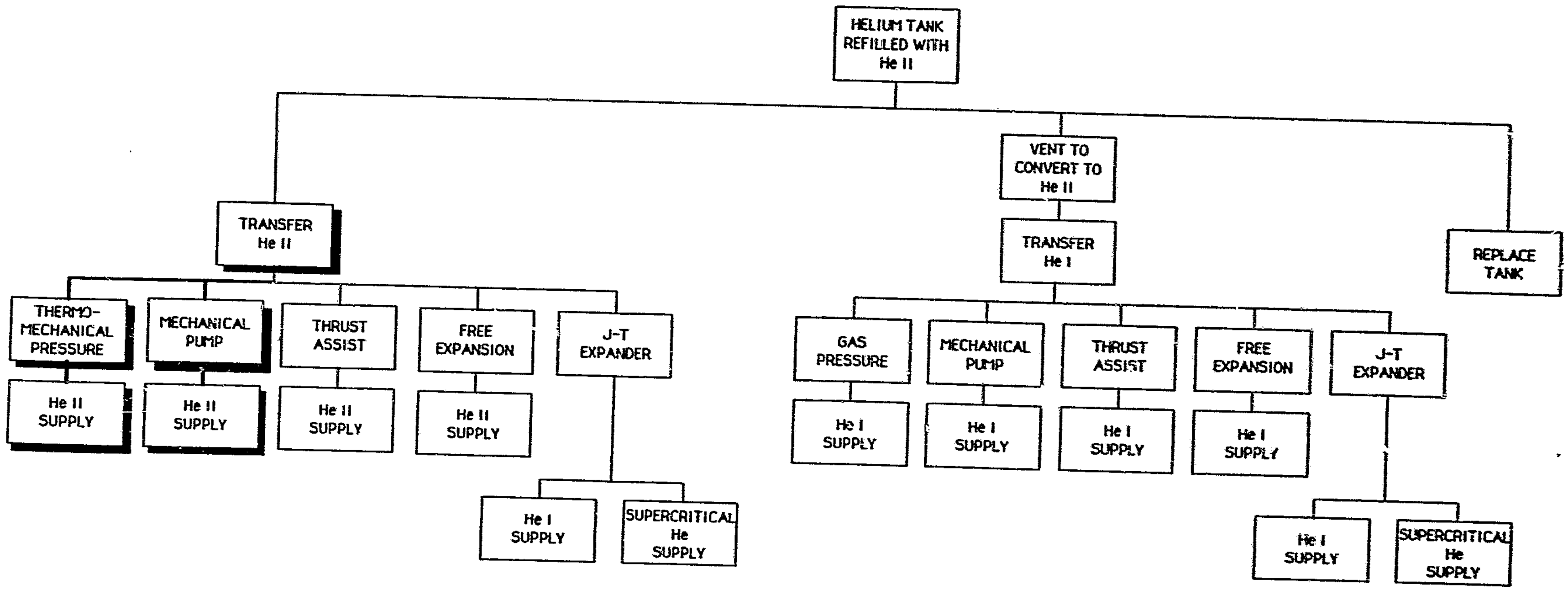

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Figure 1-3 Helium Replenishment Technique Options

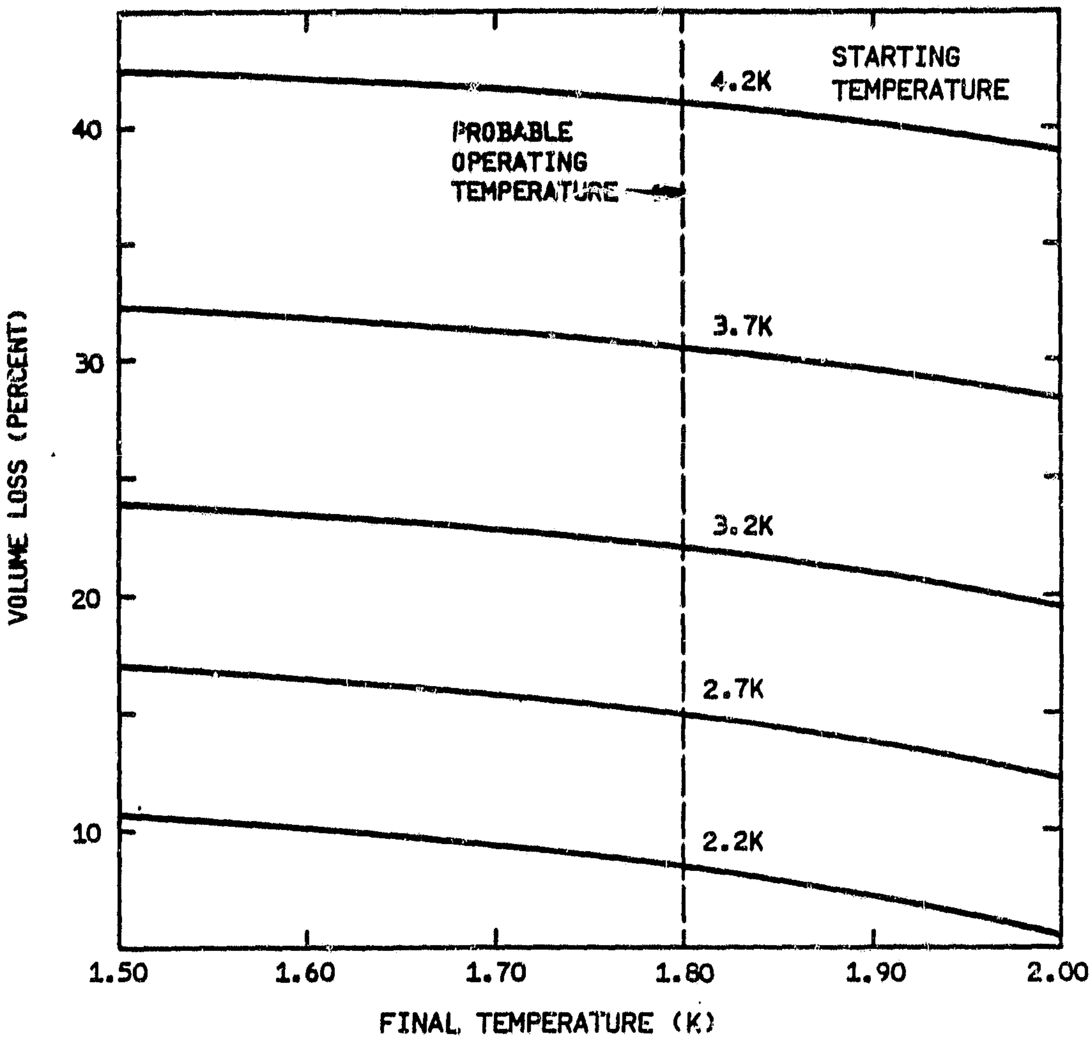

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Figure 1-4 Volume Loss in Cooling SIRTF After Transfer

its final operating temperature. For instance, this amounts to a lifetime (and ASE volume) advantage of 15 percent from transferring 1.8 K He II instead of transferring He I at 2.7 K and then cooling it to 1.8 K.

Of the 5 potential techniques for transferring He II, we have baselined the two highlighted ones because of their simplicity, and because their effect on the overall replenishment system design is so similar that parallel development would significantly reduce programmatic risk at minimal cost. Table 1-2 lists the possibilities, and summarizes the elements of the trade-off. The mechanical pump is under development by NBS in conjunction with NASA-ARC, and the thermomechanical pump is under development by BASD and NASA-GSFC.

The thermomechanical pumping technique is somewhat exotic because it is based on a physical phenomenon, the fountain effect, peculiar to He II. We review it in this report because it is unfamiliar to most aerospace professionals.

The basic phenomenon has been studied by physicists since 1938, and is illustrated in Figure 1-5. If a porous plug (tightly packed jewelers' rouge in the original experiments) submerged in He II is heated on one side, liquid is observed to move through the tiny pores from the cold side to the warmer side. This can produce either a substantial volume flow rate, as originally observed in the "fountain" illustrated, or pressures as high as a few hundred torr at zero flow rate. This is the phenomenon that underlies the operation of the porous plug vents used successfully on IRAS and the Far Infrared Sky Survey Experiment (FIRSSE).

Figure 1-6 shows the elements of a replenishment system based on a thermomechanical pump. The supply and receiver dewars are connected by a transfer line with bayonet connections. The pump is connected directly to the supply dewar, and both dewars are vented through porous plug vents. An electrical heater on the downstream side powers the pump, and controls the mass flow rate. The heat supplied boils off approximately 5 percent of the liquid

Table 1-2
LIQUID TRANSFER TECHNIQUE TRADEOFF

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Thermomechanical Pump	Simplicity, reliability due to no moving parts.	4.7% mass loss at 1.8 K
	Mass loss occurs in ASE dewar, so high-flow vent not needed in SIRTF.	Requires large vent in supply dewar.
	Easy to control flow rate.	Works with He II only.
	Static pressures up to 500 torr attainable.	
	Under development by GSFC, BASD.	
Mechanical Pump	Mass loss less than thermo-mechanical pump above 1.5 K	Reliability risk due to cold bearings.
	Familiar technology.	
	Works with He I, other cryogens.	
	Under development by NBS/ARC.	
Thrust Assist	No pump required.	Major impact on Shuttle/ Space Station operations.
		Low flow rates.
		Limited pressure available for cooldown.
Free Expansion	No pump required.	Driving pressure <38 torr may impede cool-down.
	May be used for other cryogens on Space Station.	
	Under development by LeRC.	Unknown mass efficiency.
Joule-Thomson Expansion	Intercept heat leak or remove heat from receiver dewar. Used in combination with another transfer technique.	Requires second dewar for supercritical He or He I. Subject to clogging of single small orifice.

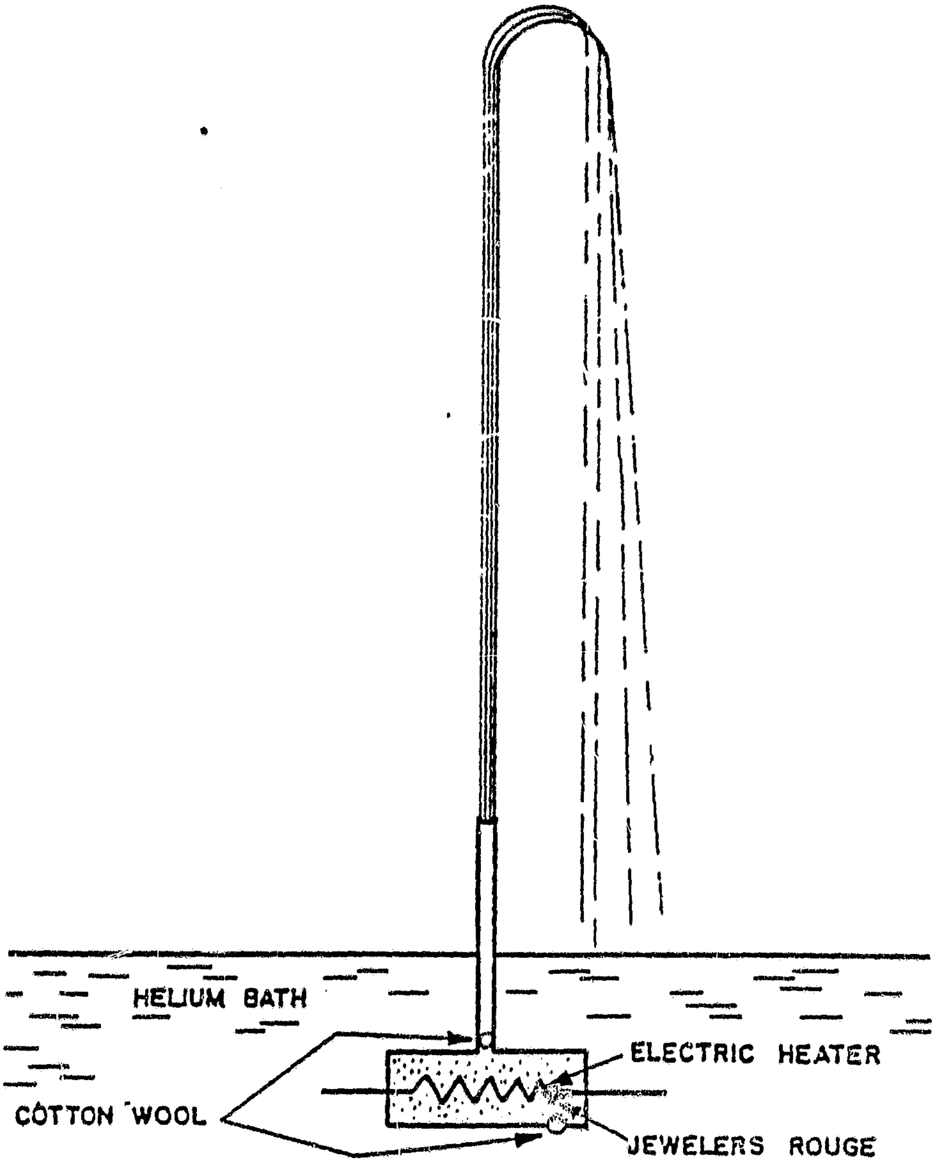

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Figure 1-5 Fountain Effect in HELIUM II

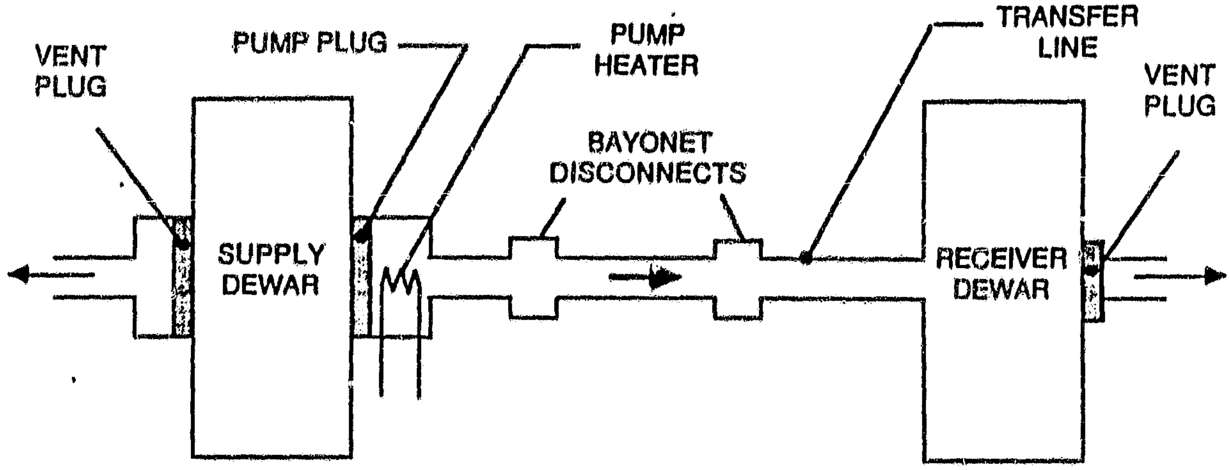

Figure 1-6 Replenishment System Based on Thermomechanical Pump

carried in the ASE, but the boiling takes place in the ASE dewar for reasons that are explained in Section 2.1.3. The volume loss must be allowed for in the design of the ASE, but does not prevent 100 percent fill of the SIRTF.

1.1.2 Modifications to SIRTF

The baseline cryogenic design of SIRTF requires some modification to permit on-orbit replenishment of the cryogen. There are changes to the plumbing, and modification of the aperture cover. The plumbing changes do affect the lifetime of the SIRTF dewar.

Plumbing Modifications

The SIRTF fluid management system must be modified from its current baseline to accommodate two new requirements:

- To permit cooldown in an acceptably short time with minimum cryogen consumption, and
- To permit filling with He II at a suitably high flow rate once the SIRTF dewar has been cooled off.

Even if the servicing strategy adopted for SIRTF assumes it will be replenished before it runs dry and starts to warm up, including the appropriate hardware modifications to permit on-orbit cooldown is a wise precaution to permit recovery if the timing of the servicing mission is not ideal.

Analysis of our experience with the cooldown of IRAS led to the development of a transient thermal model that successfully predicted the cooldown behavior of COBE in its first filling at BASD. From this analysis we found that the two principal factors in determining the cooldown efficiency are:

- Thermal conduction between the dewar and the telescope system, and

- Efficient heat transfer between the dewar and the incoming helium gas.

To achieve an efficient on-orbit cooldown, we therefore require the addition of a forced convection heat exchanger as part of the SIRTF fill line, plus optimized thermal joints within the telescope package.

Figure 1-7 shows the modified fluid management system, which includes:

- An additional loop of the fill line before it enters the main cryogen tank, acting as a forced convection heat exchanger during the initial cooldown;

- A large additional porous vent plug to accommodate high flow rates during the initial collection of He II liquid;

- A new short vent line to reduce backpressure during the initial cooldown; and

- Increased line and valve orifices (2.5 cm instead of 1.9 cm) to reduce backpressure during the initial cooldown.

The last two elements are definitely necessary to permit the use of a thermomechanical pump. The driving pressure achievable with a centrifugal pump and its design impact remain to be investigated.

Aperture Cover

A serious source of potential contamination for the SIRTF telescope optics is likely to be products of the bipropellant propulsion system of the Orbital Maneuvering Vehicle (OMV) that retrieves SIRTF from its orbit and

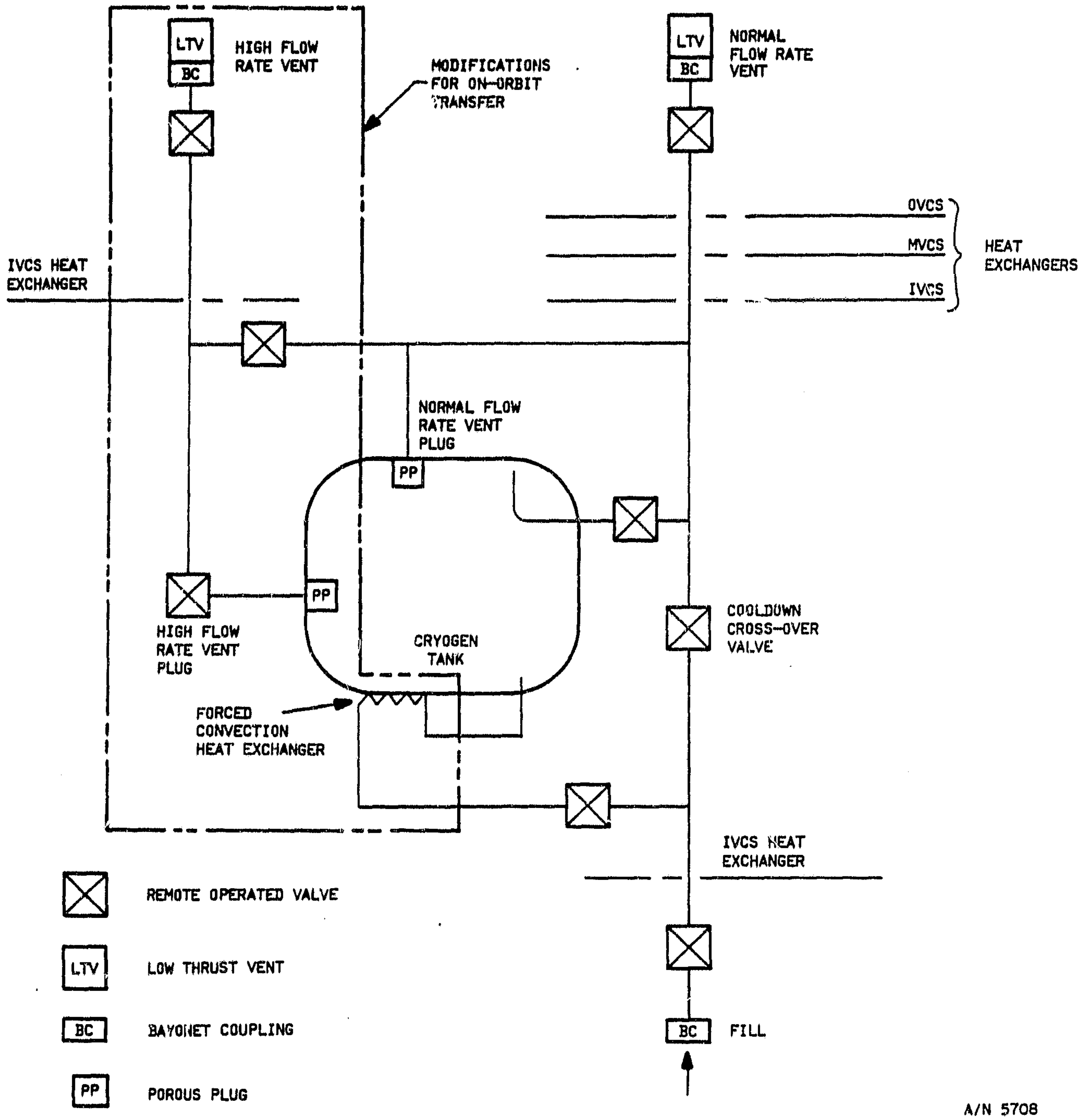

Figure 1-7 SIRTF SFHe System Modified for Replenishment

redeploys it after servicing. A shutter blade over the dewar aperture must therefore be closed before rendezvous with the OMV, and kept closed until SIRTF is redeployed and the OMV has departed.

Thermal radiation from this blade could impose a heatload on the dewar as high as 13 W, which would prevent stabilization of the dewar after replenishment. Active cooling of the shutter blade with cooling coils would be excessively complex. A blanket of multilayer insulation would reduce the radiation to 0.5 W, which would not perturb the dewar operation unacceptably.

Impact on SIRTF Performance

The modifications to SIRTF for replenishment do introduce additional heat leakage into the dewar, and therefore reduce its lifetime. The impact of the additional vent line and the increase in diameter of the fill line from 1.9 cm to 2.5 cm has been analyzed with the thermal model of SIRTF developed by BASD under the Thermal and Cryogenic Study[1] for NASA-ARC. We find that lifetime will be reduced by 7 percent for the baseline 4000 liter configuration, compared to the unmodified system.

1.1.3 Airborne Support Equipment Design Concept

The Airborne Support Equipment (ASE) used to replenish the SIRTF cryogen consists of two self-contained kits interconnected by the Shuttle or Space Station data buss, as shown in Figure 1-8. The external ASE kit is dominated by the dewar, both in terms of mass and cost. The control and monitor electronics box is mounted on the outside of the dewar, and the transfer line is stowed on it when not in use. The internal ASE kit consists of a data and command console that interfaces with the Shuttle or Space Station communications system. The overall characteristics of the ASE are summarized in Table 1-3.

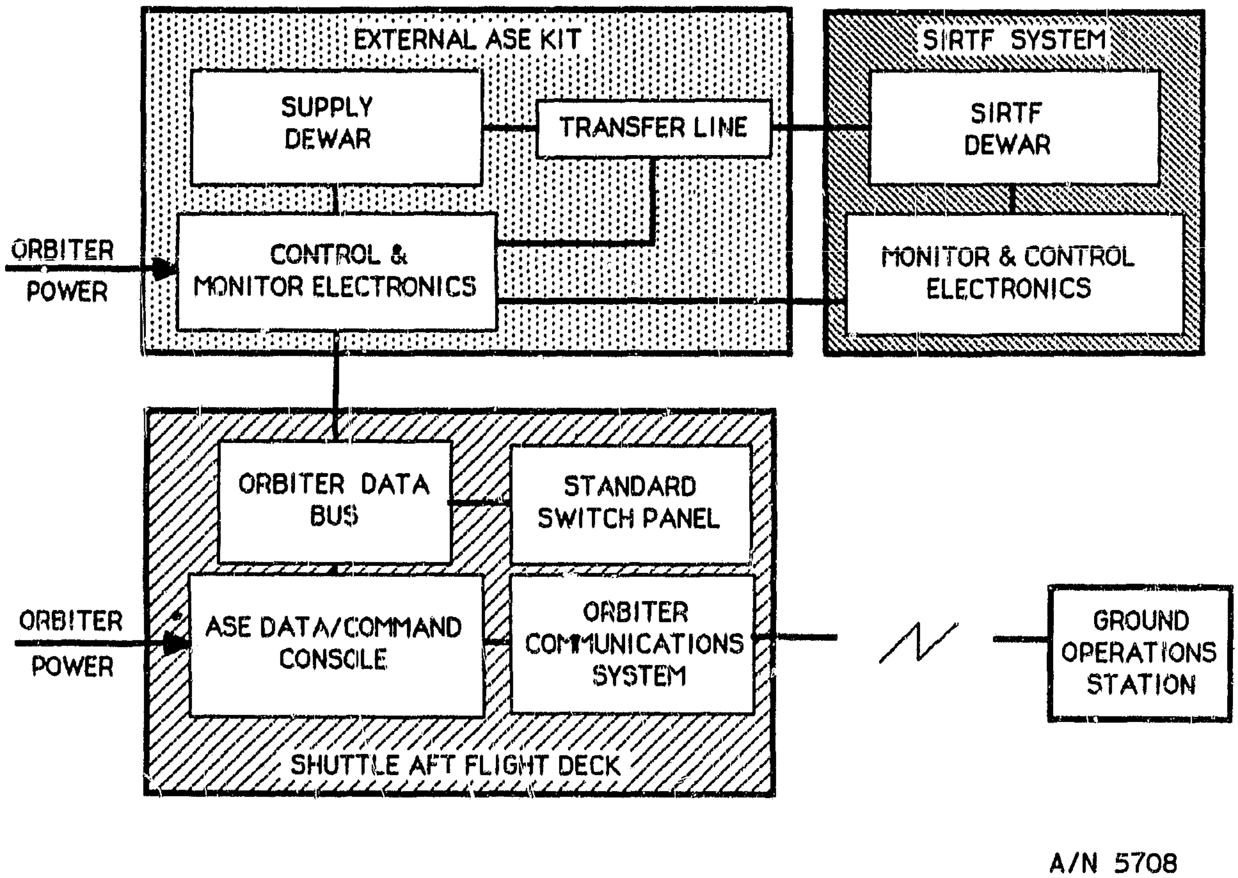

Figure 1-8 Airborne Support Equipment Elements

Table 1-3

AIRBORNE SUPPORT EQUIPMENT PROPERTIES

PARAMETER	VALUE
MASS (FULL)	2,250 KG MINIMUM(1) 4,097 KG MAXIMUM(2)
HELIUM VOLUME	5,300 LITER MINIMUM(1) 11,750 LITER MAXIMUM(2)
POWER CONSUMPTION	
EXTERNAL ASE KIT	< 2 W DURING STORAGE < 200 W MAXIMUM
INTERNAL ASE KIT	< 2 W DURING STORAGE <100 W MAXIMUM
THERMAL CONTROL SURFACE	$\alpha/\epsilon = 0.2 - 0.3$
MECHANICAL INTERFACE	SIRTF KEEL FITTINGS, ON MMS CRADLE A ON SHUTTLE. TBD ON STATION.
RMS/MRMS INTERFACE	NASA GRAPPLE FIXTURE

(1) To refill SIRTF while still cold.

(2) To cool SIRTF from 300 K and refill.

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Cryogenic Design

The overall cryogenic layout of the ASE when connected to the SIRTF for replenishment is shown in Figure 1-9. The system design would be nearly the same using either the thermomechanical pump taken as our baseline, or the mechanical pump alternate. The fluid management system shown provides functional redundancy for safety, but not component redundancy. If component redundancy is ultimately required for handling even inert fluids on Space Station, the plumbing system would have to be modified accordingly.

One of the first dewar design tradeoffs is how much design and manufacturing cost should be devoted to a high-efficiency insulation. We explored three different levels of insulation technology which would give cryogen loss rates of 0.1, 0.2 and 0.5 percent per day. These span the range from IRAS-level technology to commercial storage dewar technology. The assumed 60-day hold time on orbit (plus 30 day margin) would require a volume as much as 50 percent larger using the commercial techniques rather than the best IRAS-derived ones. We therefore baselined an IRAS-type system with 4 vapor-cooled shields, at an assumed loss rate of 0.1 percent per day. Detailed modeling of an interim system using this configuration showed an anticipated loss rate of about 0.07 percent per day, so the sizing used here is conservative.

The ASE dewar is designed with a special high flow rate vent to accommodate the high boiloff rate which accompanies high-rate transfers using the thermomechanical pump. Detailed simulations have shown 1000 liters per hour to be feasible, so we are baselining this rate in our design and operational timelines. The heat input from a centrifugal pump would raise the temperature of the liquid entering the SIRTF dewar, but would not place any unusual requirements on the ASE vent lines.

Mechanical Design

Mechanical designs have been worked out for the two limiting cases for the ASE:

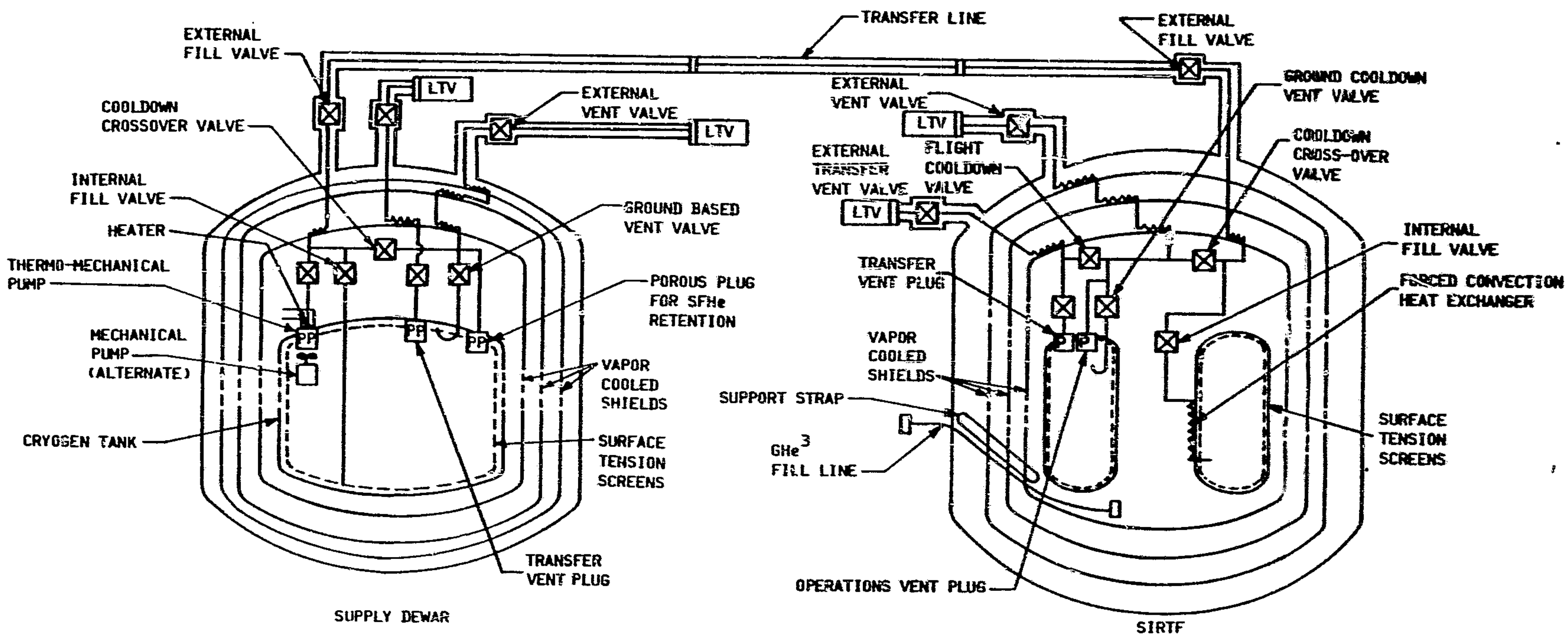

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Figure 1-9 Cryogen Replenishment System

- 5300 liter capacity, for replenishing SIRTF before it runs dry, and
- 11,750 liter capacity, for replenishing SIRTF after it has warmed up to 300 K.

This larger version is the one that would be needed for a servicing mission that includes instrument changeout.

A tradeoff on dewar shape led to the two cylindrical tank configurations shown in Figures 1-10 and 1-11. This shape was chosen to minimize the length of Shuttle bay required for launch, thereby minimizing overall mission costs. The total mass when full is 2550 kg for the small version, and 4097 kg for the large one. Weight relieving measures could be applied, but may not be cost effective since the mass per unit length is near the 16.1 kg/cm optimum Shuttle loading.

The special hardware which will be required to dock SIRTF on Shuttle for servicing can be derived from that developed by GSFC for the Multi-mission Modular Spacecraft (MMS). Figure 1-12 shows a modified version of the Cradle A that provides an attachment for mating with the keel fitting used for launching SIRTF, plus stowage for the focal plane instrument and external SIRTF electronics Orbital Replaceable Units (ORU's). Figure 1-13 shows SIRTF docked to Shuttle using the MMS Cradle A.

For servicing on the Space Station, we assume that hardware will exist for docking various payloads using their Shuttle sill and keel fittings. Figure 1-14 shows SIRTF docked to the Station using a 3-point trunnion mount, although a single-point mount such as shown in Figure 1-12 would probably be adequate.

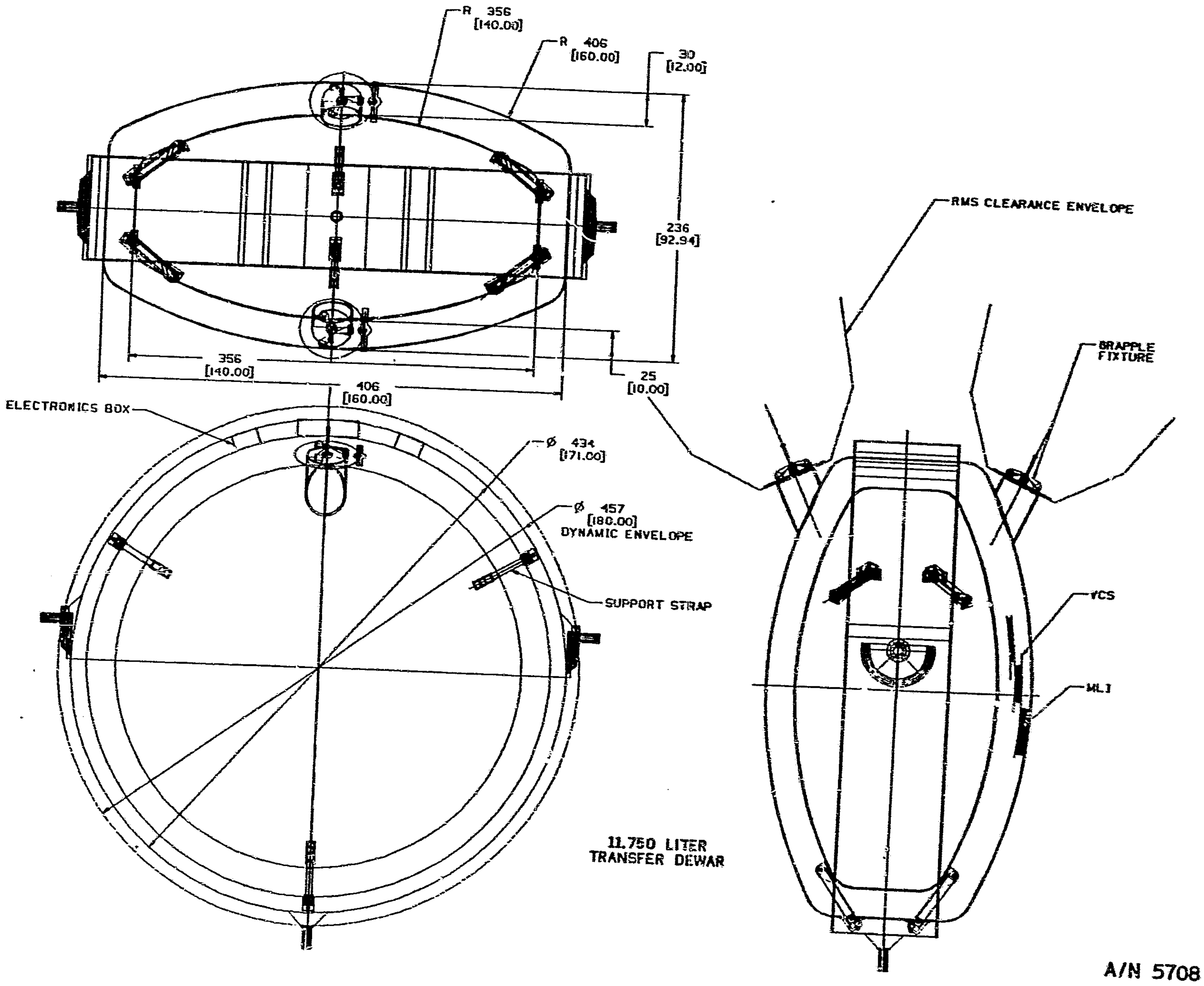

Figure 1-10 11750 Liter ASE Dewar

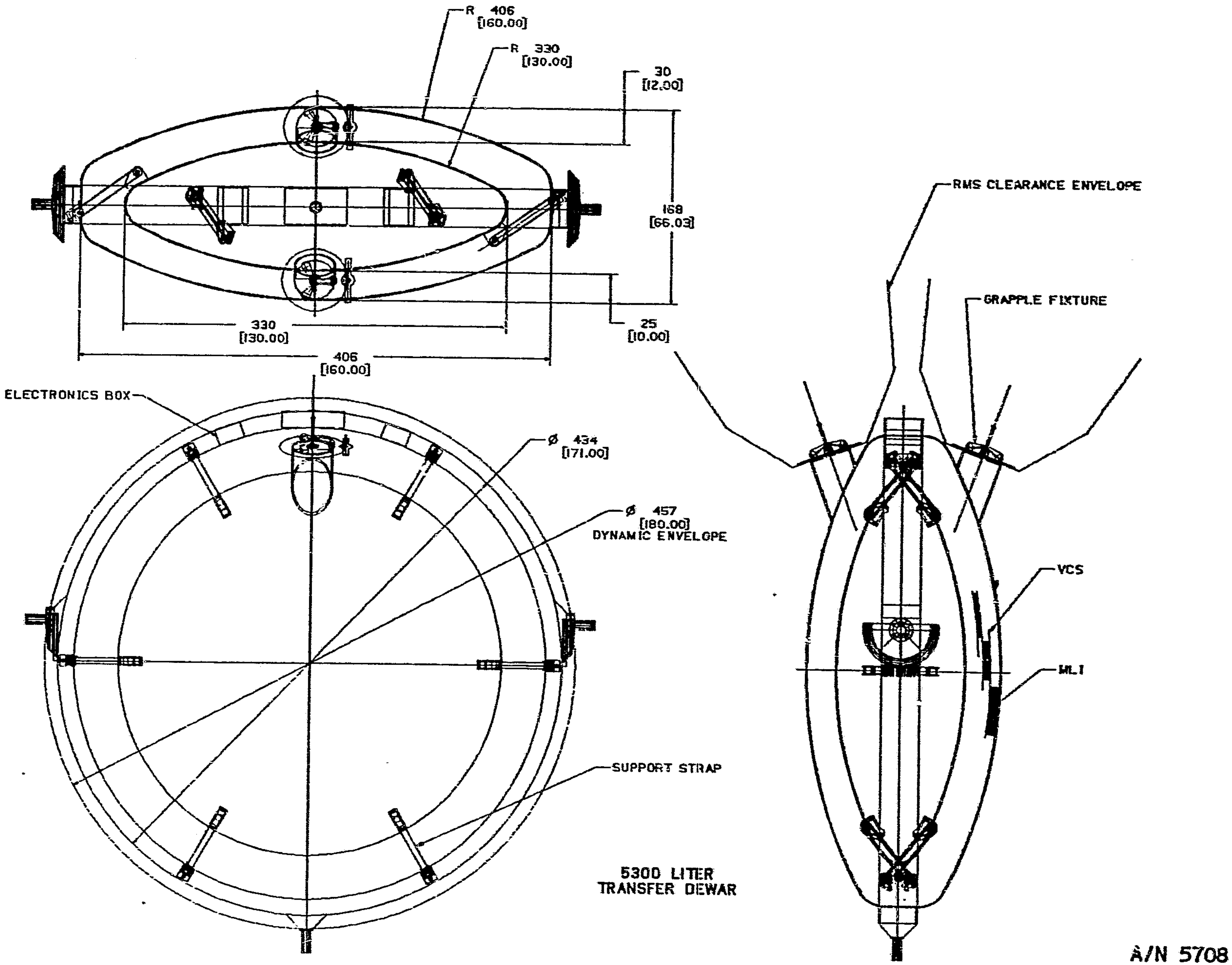

Figure 1-11 5300 Liter ASE Dewar

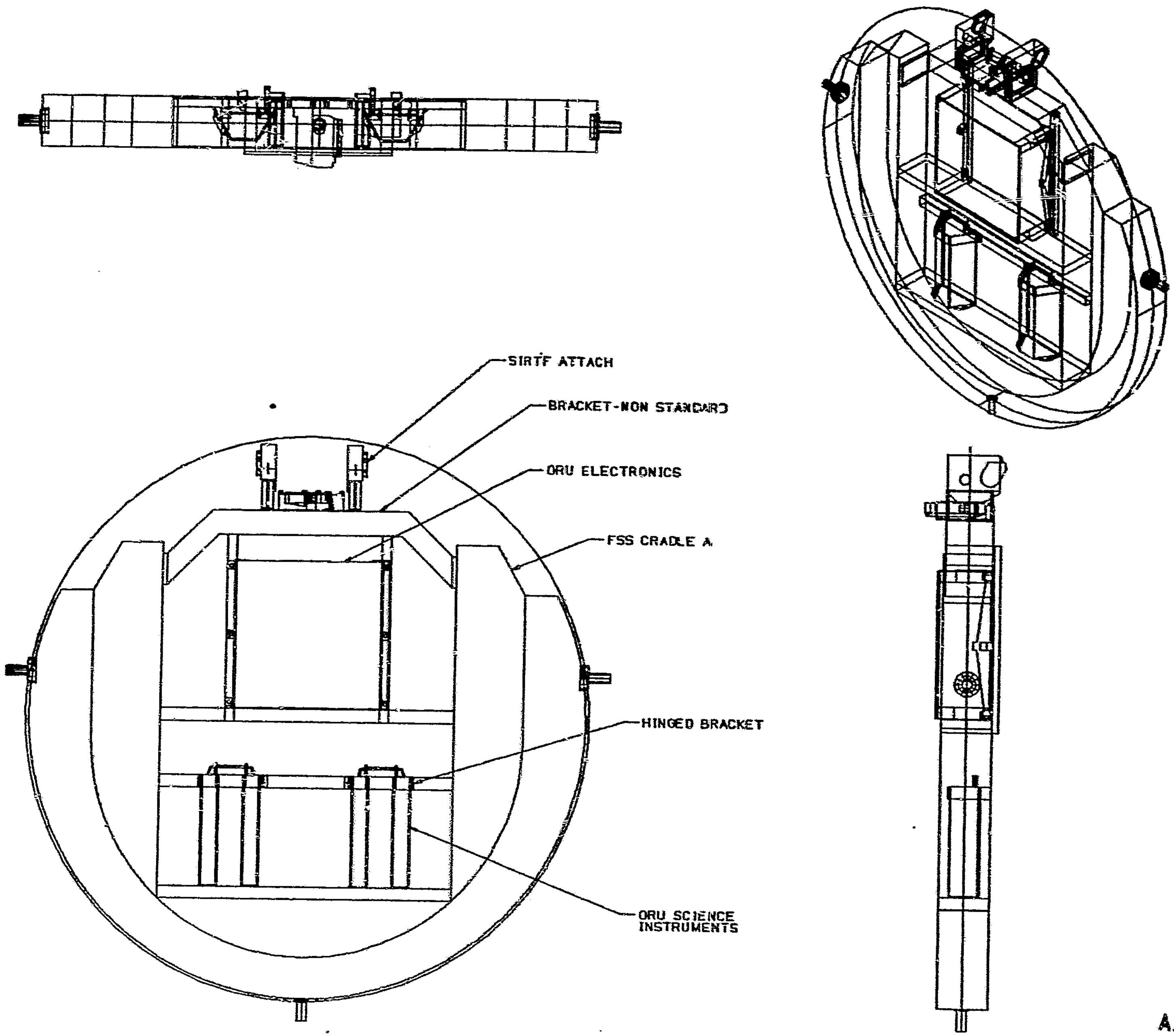

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Figure 1-12 FSS Modified for SIRTF

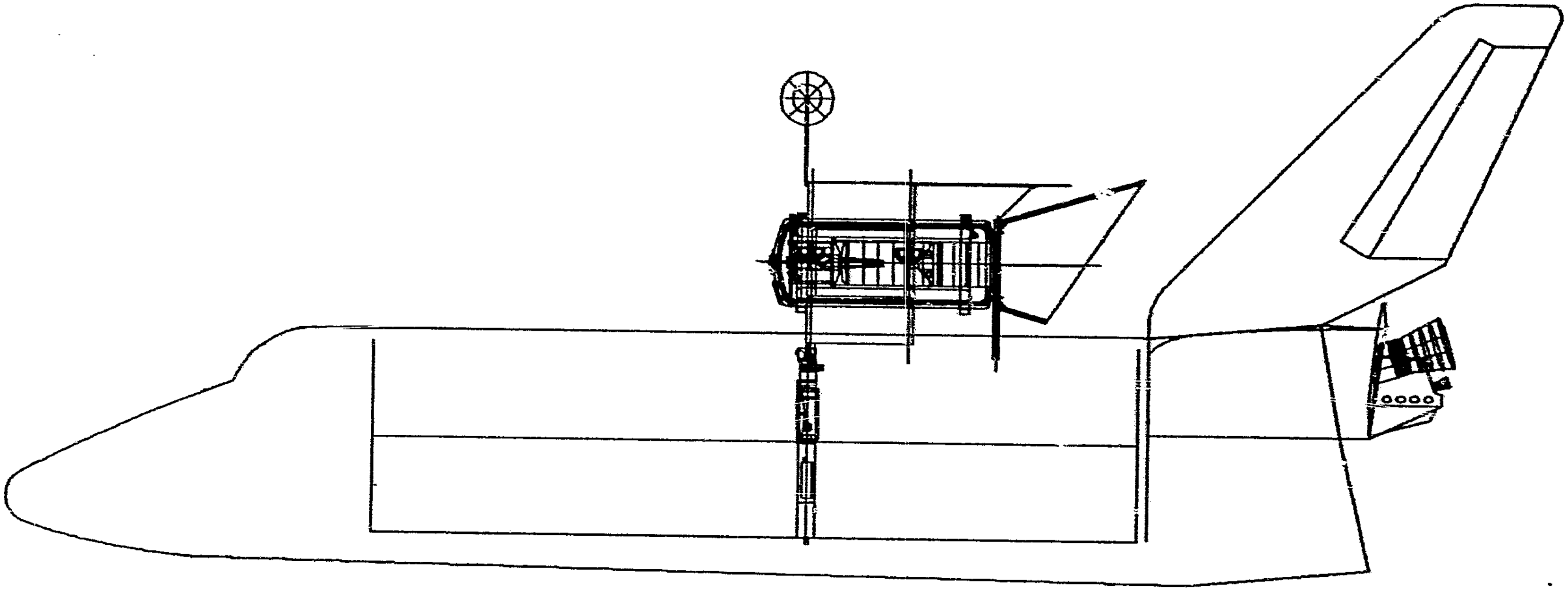

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Figure 1-13 Replenishment on Space Shuttle

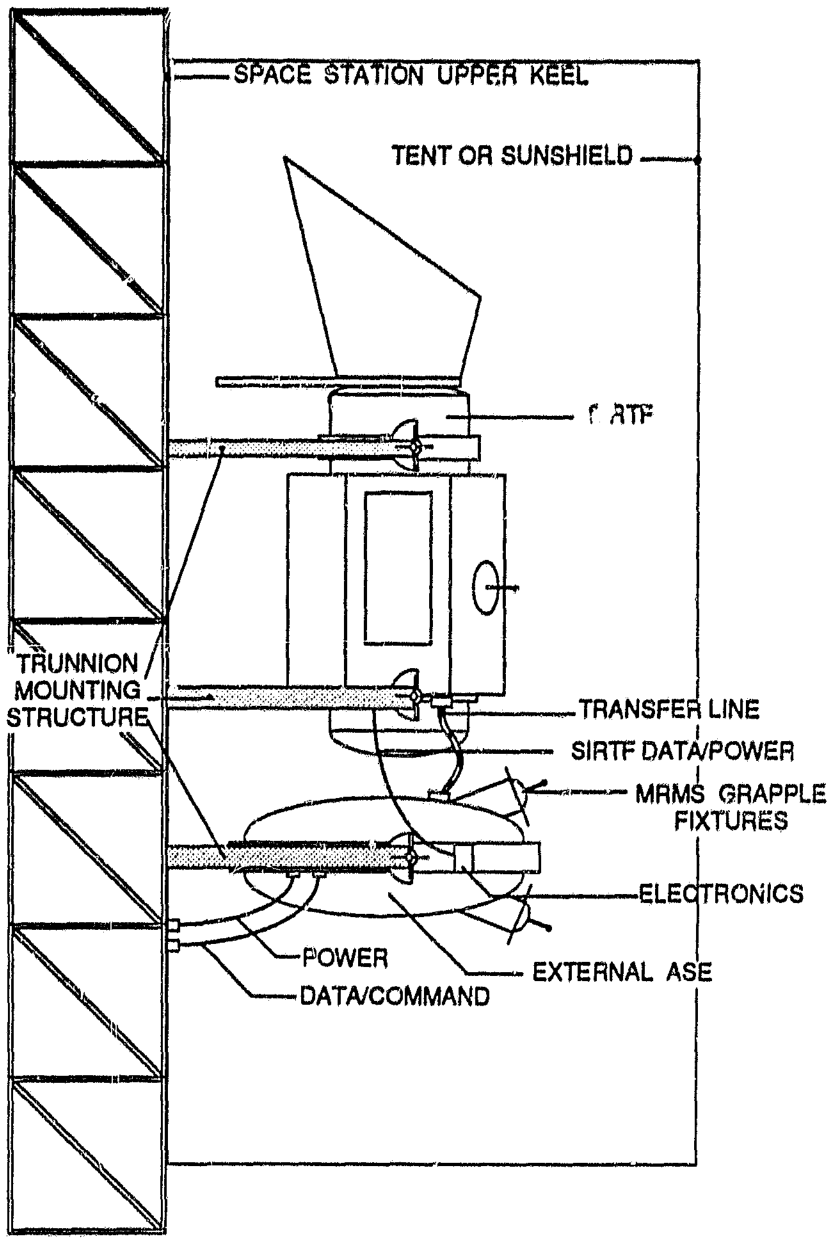

Figure 1-14 Replenishment on Space Station

Electrical Design

Figure 1-15 shows that the electrical subsystem of the ASE consists of two parts: the sensor and control electronics mounted on the dewar, and the control and data handling console located inside the Shuttle cabin or the Space Station Logistics Module. The Data/Command Computer controls the acquisition of data and permits partially or fully automated control sequences to be used during the transfer operation. Telemetry permits control from Ground Operations Control. Total peak power consumption would be less than 200 W.

1.1.4 Servicing Alternate Cryogenic Systems

After developing concepts for replenishing the baseline SIRTF He II cryogenic system, we briefly explored servicing two alternate systems: a dual-cryogen version of SIRTF that uses solid hydrogen to intercept the bulk of the dewar heat load at 10 K, and a small helium-3 subsystem used to provide temperatures below 1 K for long-wavelength detectors in one of the focal plane instruments.

Dual-Cryogen Systems

The dual-cryogen system described in the SIRTF Phase A Free Flyer Concept has a 1650 liters of solid hydrogen that must be replenished. Using the Cryogenic Fluid Management Facility (CFMF) study[8] done for NASA-LeRC as our guide, we have baselined free expansion (referred to as "thermodynamic fill" in the CFMF study) as the technique for transferring liquid hydrogen into SIRTF. The remaining questions to be addressed here are the ASE needed, the method for cooling the hydrogen tank, and the method for converting the liquid to solid in SIRTF.

One possibility for transporting the liquid hydrogen is to use six identical copies of the CFMF 600 liter dewars. A dual-cryogen ASE incorporating a 2,200 liter hydrogen dewar dedicated to SIRTF would be needed for a system

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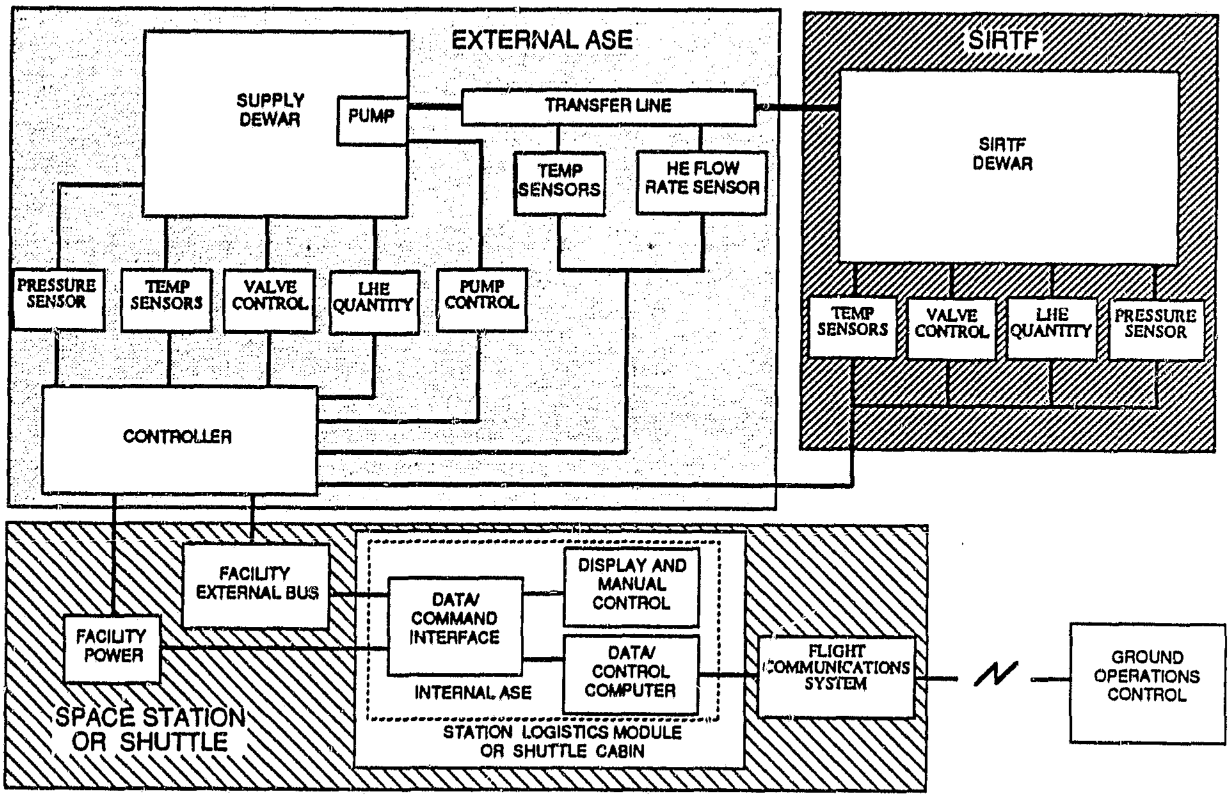

Figure 1-15 ASE Electronics Configuration

capable of replenishing SIRTF before it runs dry. For replenishment based on Space Station, it may be possible to use the liquid hydrogen stored for propulsion, rather than build a dedicated hydrogen dewar for SIRTF.

The two basic options for converting the liquid hydrogen to solid are to vent it to space ("blowdown"), or to cool it with coils supplied with He II. The blowdown technique is the simplest, but results in about 30 percent empty volume in the dewar. This will be a severe impact on the SIRTF lifetime, unless SIRTF is initially designed with a correspondingly larger hydrogen tank to compensate. Cooling the hydrogen with He II would require an additional 5,600 liters of helium.

Helium-3 Subsystem

In order to explore the implications of servicing helium-3 subsystems, we examined filling a 3 liter volume based on the heat loads presently baselined for the Multiband Imaging Photometer for SIRTF (MIPS), and also a volume as large as 100 liters. The two basic options are to transfer liquid directly, or to transfer gas and condense it inside SIRTF. Because the gas transfer technique is well-developed and practical, there is no apparent reason to incur the development costs and operational complexity associated with transferring the helium-3 as a liquid.

The gas fill technique is the standard practice in low-temperature laboratories. The three limitations on its use are the size of the compressed gas bottles required, the time it takes the gas to flow through the capillary into the dewar, and the volume of He II consumed in condensing it. The small 3 liter system would require less than one full Type 1C (126 liter) bottle of gas, and consume 150 liters of He II in condensing it to liquid. The 100 liter system would require 3 bottles, and as much as 4,900 liters of He II. (The He II consumption given here is a worst-case limit, using only the heat of vaporization to cool the incoming gas. A counter-flow heat exchanger would reduce the He II consumption substantially.) Total replenishment and condensation time would be less than 2 hours for the smaller system.

1.2 INSTRUMENT CHANGEOUT

The first question that arises in servicing the focal plane instruments or other cold mechanisms inside the SIRTF dewar is whether the servicing can be performed while the dewar is still cold, or whether it must first be warmed to near room temperature. Then the two principal tasks remaining are to develop a practical means of giving access to them, and to assess the design impacts of providing for serviceability.

Opening the SIRTF dewar for servicing while it is still cold is essentially ruled out by one overriding fact: the Extravehicular Maneuvering Units (EMU's) used by the astronauts discharge massive amounts of oxygen that would seriously contaminate the optics of the instruments and the telescope if exposed at temperatures below about 170 K. Redesign of these suits to eliminate this problem would constitute a major development cost. Other practical considerations regarding alignment and lubrication of fasteners lead us to recommend warming SIRTF electrically to near 300 K before rendezvous for servicing. The penalty in cooldown time and volume of cryogen required do not seriously impact the servicing mission.

1.2.1 Dewar Access

The two basic options for providing access to the focal plane instruments are to either remove the complete telescope and instrument assembly from the mouth of the dewar, or to provide an opening in the back end of the dewar. Removing the complete telescope assembly is awkward, requires provisions for stowing the 5.2 m assembly outside the dewar, and exposes the telescope optics to serious contamination risks. Therefore we recommend modifying the SIRTF dewar to provide for rear access.

Figure 1-16 shows a swing-open door concept that minimizes demands on the astronauts servicing the instruments. Thermal contraction provides the pressure to lock the removable sections of the vapor-cooled shields to the fixed parts with adequate thermal conductivity. All multilayer insulation blankets are held captive, with their edges controlled by a Kapton band.

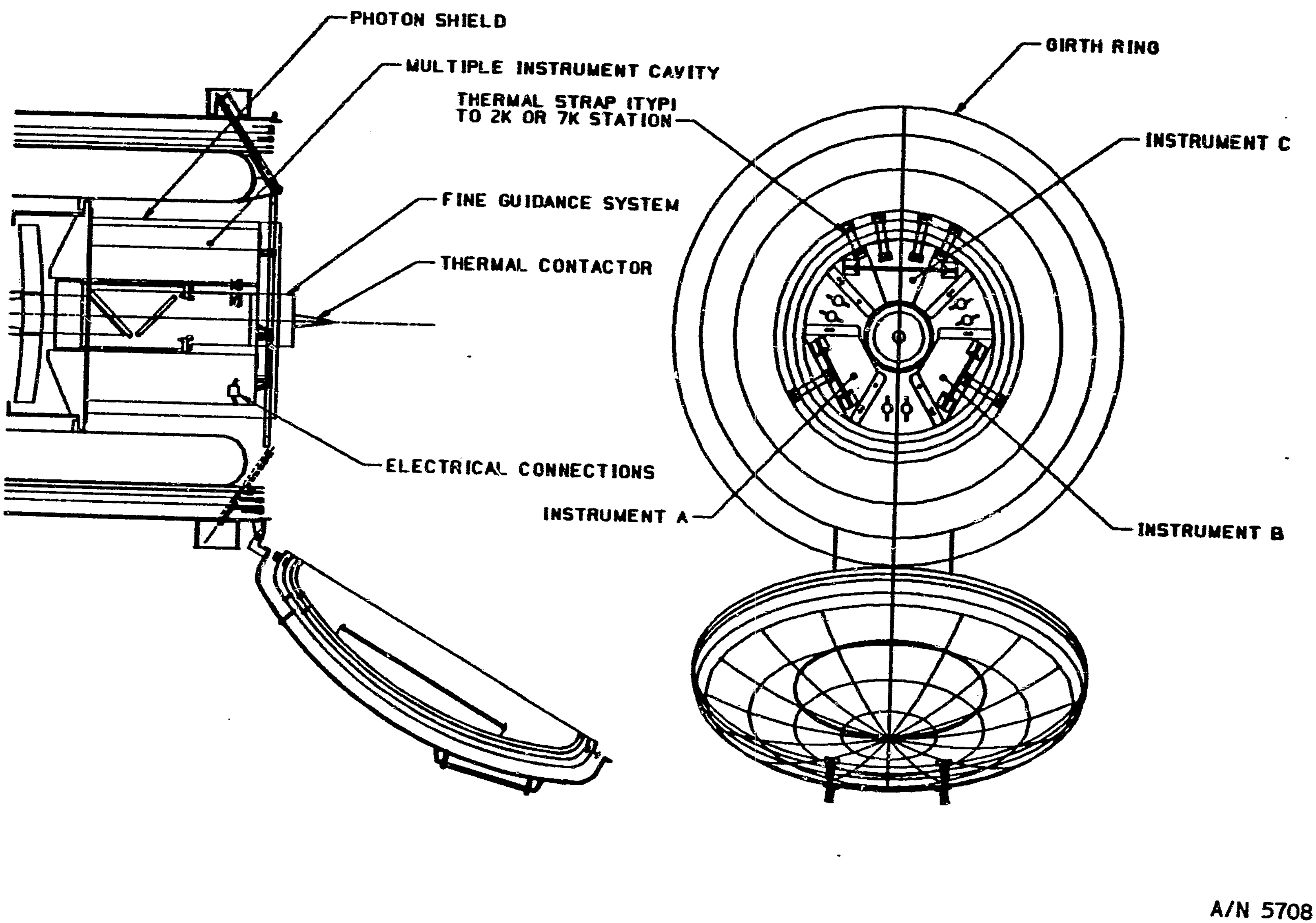

Figure 1-16 Instrument Rear Access

The principal impact on the cryogenic performance of the SIRTF dewar due to this modification is the additional radiation leakage due to the gap of about 3 mm at the joint in each MLI blanket. Our thermal modeling shows that this will reduce the lifetime of the replenishable version of SIRTF from 2.5 years to 2.0, a decrease of 20 percent.

1.2.2 Servicing Cold Mechanisms

After access is designed into the SIRTF dewar, several other requirements must be taken into account in designing those mechanisms which are to be serviced. The operation impacts of servicing them are discussed in a later section.

Focal Plane Instruments

The modifications to the focal plane instruments to accommodate on-orbit changeout amount to an extension of those design features which would simplify their removal and replacement during ground integration. These features are:

- Guide rails to simplify insertion,
- Thermal strapping to eliminate the need for thermal gasket material under the structural mounting points,
- Handles with clearance for gloved hands,
- Round corners to protect astronauts' suits, and
- EVA-rated electrical connectors.
- Non-black coatings or marks on outside of instruments and inside MIC to enhance visibility.

The space taken up by the handles and rounded corners will impose additional packaging constraints on the design of the instruments, and therefore could force compromises in their optical performance. The separation of the structural mounting and thermal contact functions, however, amounts to good instrument design practice. One possible layout showing the locating pins and thermal straps is shown in Figure 1-17.

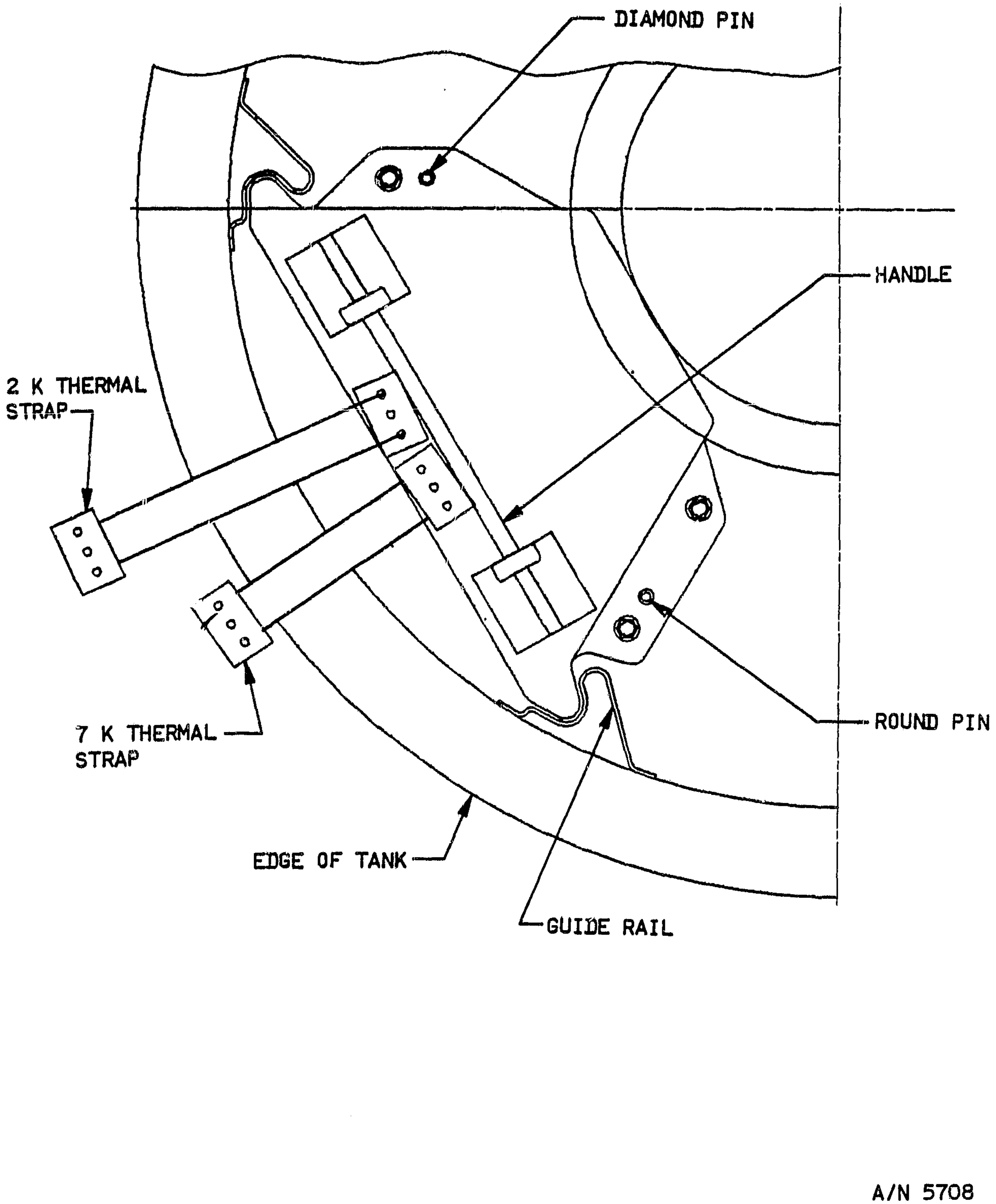

Figure 1-17 Instrument Mounting

Other Cold Mechanisms

Because the SIRTF fine guidance sensor (FGS), rotating beamsplitter, and chopping secondary mirror are essentially undefined at this time, analysis of servicing them amounts to analyzing access to them. The FGS and rotating beamsplitter are inside the MIC, so rear access into the dewar is enables them to be reached conveniently. It is presently assumed that the FGS is supported by the beamsplitter assembly, so the detailed design will determine whether it is practical to service them independently or whether they should be combined in one replaceable module.

The baseline SIRTF design has the motor-driven cryogenic valves placed at the front end of the dewar for ease of manufacturing. Modifying the dewar for rear access to the instruments makes it practical to move the valves to the rear, where they can also be serviced. Provisions for eliminating thermoacoustic oscillations during ground operations would need to be made. Designing the valves themselves for replacement introduces risks of leaks, but designing the motor and gear head units for replacement would be straightforward.

Servicing the chopping secondary mirror of the telescope poses serious design challenges because of its location inside the telescope baffles. Replaceability using special long tools would become a driver on the design of the mirror, and may be incompatible with the requirements for precise positioning and high-conductance heat sinking. Including redundant solenoid windings and position sensors may be the most practical way to ensure its long-term reliability.

1.3 MISSION ANALYSIS

In order to understand the operational aspects of on-orbit servicing of SIRTF, we analyzed the following:

- Mission scenarios for cryogen replenishment and instrument changeout, based on the Shuttle and on the Space Station.

- Operational sequences and timelines associated with these scenarios,

- Interfaces, operational constraints, and requirements of the hardware elements, and

- Impacts of human interface, including EVA and safety requirements.

The net conclusion is that servicing SIRTF is feasible from either the Shuttle Orbiter or from Space Station. Table 1-4 shows that the timelines for either cryogen replenishment alone or for instrument changeout followed by cooldown and replenishment fit within the nominal 7-day Shuttle mission. The times shown here allow for the normal crew rest period schedule with no work scheduled while any of the crew are resting, and still permit some flexibility, to deal with unexpected contingencies.

For purposes of this study, it was assumed that the servicing operations would be human-tended, with minimum use of remotely operated equipment. Plumbing connections and the electrical umbilical would be manually connected and disconnected. A remotely operated shutter blade would be closed over the telescope aperture before rendezvous with the Orbital Maneuvering Vehicle (OMV), but an astronaut would manually apply and remove a cover (possibly a flexible "shower cap") for the sunshade. Using the Remote Manipulator System (RMS) arm to remove the sunshade cover appears easy, and would shorten the Shuttle-based changeout mission by about 7 hours. The principal safety issue revolves around potential damage to the astronauts' suits by cold surfaces or leaking cryogen, and the principal contamination hazard comes from water and particulates emitted by the suits.

Table 1-4

SUMMARY OF SERVICING MISSION TIMELINES

MISSION	SHUTTLE-BASED TIME[1,2] (DAYS)	SHUTTLE-BASED EVA'S	STATION-BASED TIME[1] (DAYS)	STATION-BASED EVA'S
Cryogen Replenishment				
SIRTF Still Cold	3.2	2	3.1	2
SIRTF Warmed to 150 K	3.8	2	4.1	2
Instrument Changeout and Cryogen Replenishment	6.2	3	6.4	3

(1) Includes two round trips by OMV to 900 km orbit.
(2) Includes Shuttle launch and return.

Because of the need for assessing the impacts on the Space Station, a summary of the Station-based servicing missions is included as a stand-alone document in Appendix A. It focuses specifically on the Space Station activities, with mention of the Shuttle only as a means of transportation of the ASE to and from the Station.

1.3.1 Cryogen Replenishment Operations

Before servicing SIRTF from the Shuttle, the OMV must be used to retrieve it from its 900 km orbit. The total weight of the OMV and the ASE are well within the capability for Shuttle delivery to a 400 km orbit, so shared Shuttle missions are possible. The RMS is used to capture SIRTF and mount it on the modified Cradle A in the Orbiter bay. After covering the sunshade and connecting the transfer line and umbilical, the cooldown cryogen transfer takes place. If SIRTF has been allowed to run dry, it will have started to warm up to its outer shell temperature of about 200 K. To assess this impact, we have examined one timeline that allows for cooling SIRTF from 150 K before transferring helium. After disconnecting and removing the sunshade cover, the OMV is used to redeploy SIRTF. The RMS is used to capture the OMV and return it to the Shuttle bay.

Replenishing the SIRTF cryogen at the Space Station is essentially similar, with some hardware differences and relaxed crew scheduling constraints. The Mobile Remote Manipulator System (MRMS) will be used to transfer the ASE from the Shuttle delivering it to its storage location, and then from the storage location to the servicing area. Shuttle-style rail and keel mounting fittings are assumed to be available at various locations on the Station for attaching the ASE and SIRTF. Some sort of enclosure around the servicing bay is assumed. The Station data buss will be used to communicate between the external ASE kit and the control console inside the manned module.

1.3.2 Instrument Changeout Operations

Changing out focal plane instruments in addition to replenishing the cryogen imposes the most severe time constraints on the Shuttle-based servicing mission. A separate EVA is required for instrument changeout, and extra cooldown time is required since SIRTF must be warmed to 300 K. It is possible to accomplish this mission in 6.2 days with some contingency time available.

Figure 1-18 shows one possible arrangement of the hardware in the Orbiter bay, with a separate carrier for SIRTF instruments and servicing tools. It may be possible to save space in the bay by carrying these items on the A Cradle, providing that clearance for crew access can be worked out. The RMS would position the Manipulator Foot Restraint (MFR) as a work platform for the astronaut for instrument changeout.

Instrument changeout on the Space Station is essentially similar, except that the operation would be performed in a servicing bay tent, and much greater schedule flexibility would improve the capability of coping with unexpected difficulties. The contamination environment inside the servicing tent will need to be examined carefully to assess the impact of particulates from the tent, and the effect of confining the water vapor from the suits.

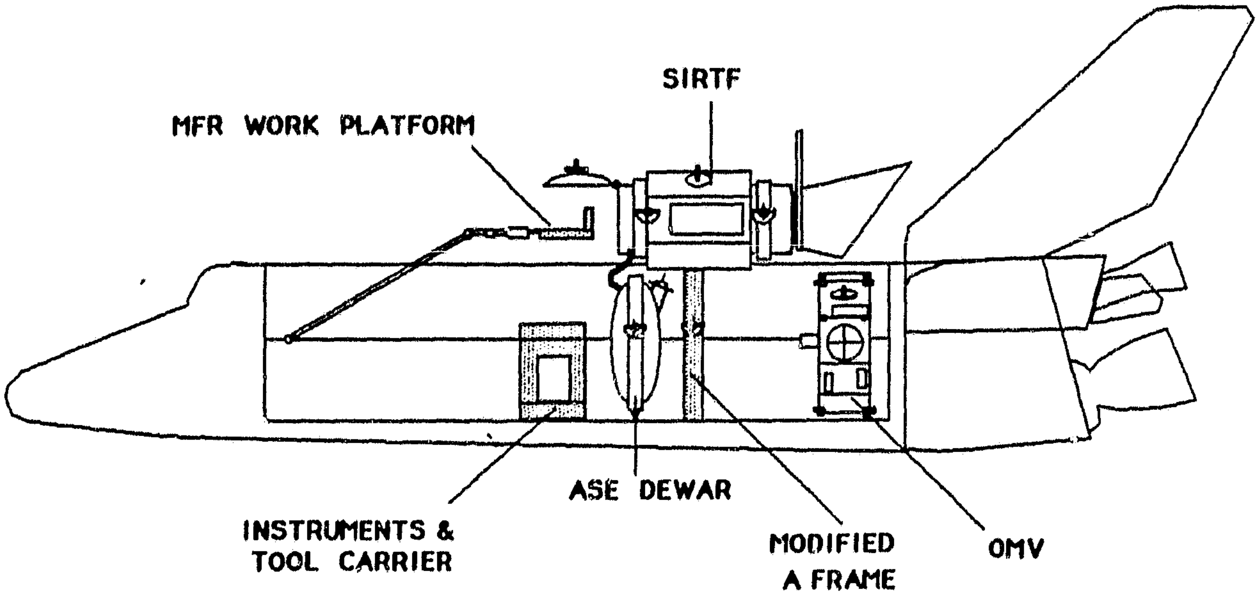

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Figure 1-18 Instrument Changeout Configuration on Orbiter

Section 2
CRYOGEN REPLENISHMENT

This section discusses the airborne support equipment (ASE) hardware required for cryogen replenishment. The baseline SIRTF for which it is designed is an all-liquid helium system; the tradeoffs and designs are therefore developed on that basis. The impact of servicing a dual-cryogen SIRTF that also employs solid hydrogen is addressed separately. Servicing a small helium-3 system used to produce temperatures less than 1 K in the SIRTF focal plane is also discussed.

2.1 SYSTEM-LEVEL TRADEOFFS

Two basic decisions must be made before cryogen replenishment hardware and operations can be developed or analyzed. These are:

- What is the basic replenishment scenario, and
- What technique will be used to transfer the cryogen into the SIRTF dewar.

After addressing these two questions, this section will review the thermomechanical pump transfer technique because it may not be familiar, and because it is a strong candidate for use in replenishing superfluid helium systems in space. The replenishment of cryogenic systems that also use hydrogen or liquid helium-3 will be addressed in Sections 2.5 and 2.6 below.

2.1.1 Mission Concept Options

There are two basic scenarios possible for a SIRTF cryogen replenishment mission:

- Filling SIRTF directly from a tank filled on the ground and transported to orbit, and

- Filling SIRTF from a permanently orbiting cryogen storage facility, which is in turn filled from tanks launched from the ground.

Various possible concept choices are shown in Figure 2-1, and the one chosen as the study baseline is highlighted. Since the storage tank constitutes the principal element of the airborne support equipment (ASE) defined in this study, the basic choices regarding the mission concept will be addressed here. The configuration chosen for the study baseline is not the only possible one, and some alternate possibilities are briefly discussed.

The most straightforward approach to replenishing SIRTF is to fill the ASE dewar on the ground, launch it full, and fill SIRTF directly from it. The alternative is to establish a permanently orbiting cryogen storage facility that is periodically resupplied from the ground. The choice depends on the expected replenishment frequency for SIRTF, and whether other cryogenic payloads would share use of the replenishment facility.

SIRTF is baselined to have life of 2 years before requiring replenishment, and a life as long as 5 years is believed to be possible.[1] Given such a long period between replenishment operations, it is unreasonable to establish a permanently orbiting facility for SIRTF alone. The cost penalty of this option is illustrated by exploratory calculations which show that a total of 11,500 liters of helium would need to be transported to such a facility to allow it to replenish a nearly empty SIRTF, compared to only 5300 liters for the highlighted option.

The next choice is the maximum time that the helium will be stored on orbit before filling SIRTF. This time must be long enough to allow rendezvous with SIRTF, taking into account the launch windows set by the orbit dynamics and the logistics of scheduling Shuttle flights, plus recovery of SIRTF from its operational orbit and redeployment with the OMV. Three possible choices are shown in Figure 2-1, and explored in Table 2-1.

Table 2-1

ASE ON-ORBIT STORAGE LIFE TRADEOFF

DESIGN STORAGE LIFE	VOLUME* (liters)	COMMENTS
1 MONTH	5,100	
2 MONTHS	5,300	SELECTED AS BASELINE
12 MONTHS		
PASSIVE COOLING	9,750	
ACTIVE COOLING	>5,100	DEVELOPMENT/RELIABILITY PENALITIES,

* REQUIRED TO FILL 4,000 LITER NEARLY-EMPTY SIRTF.

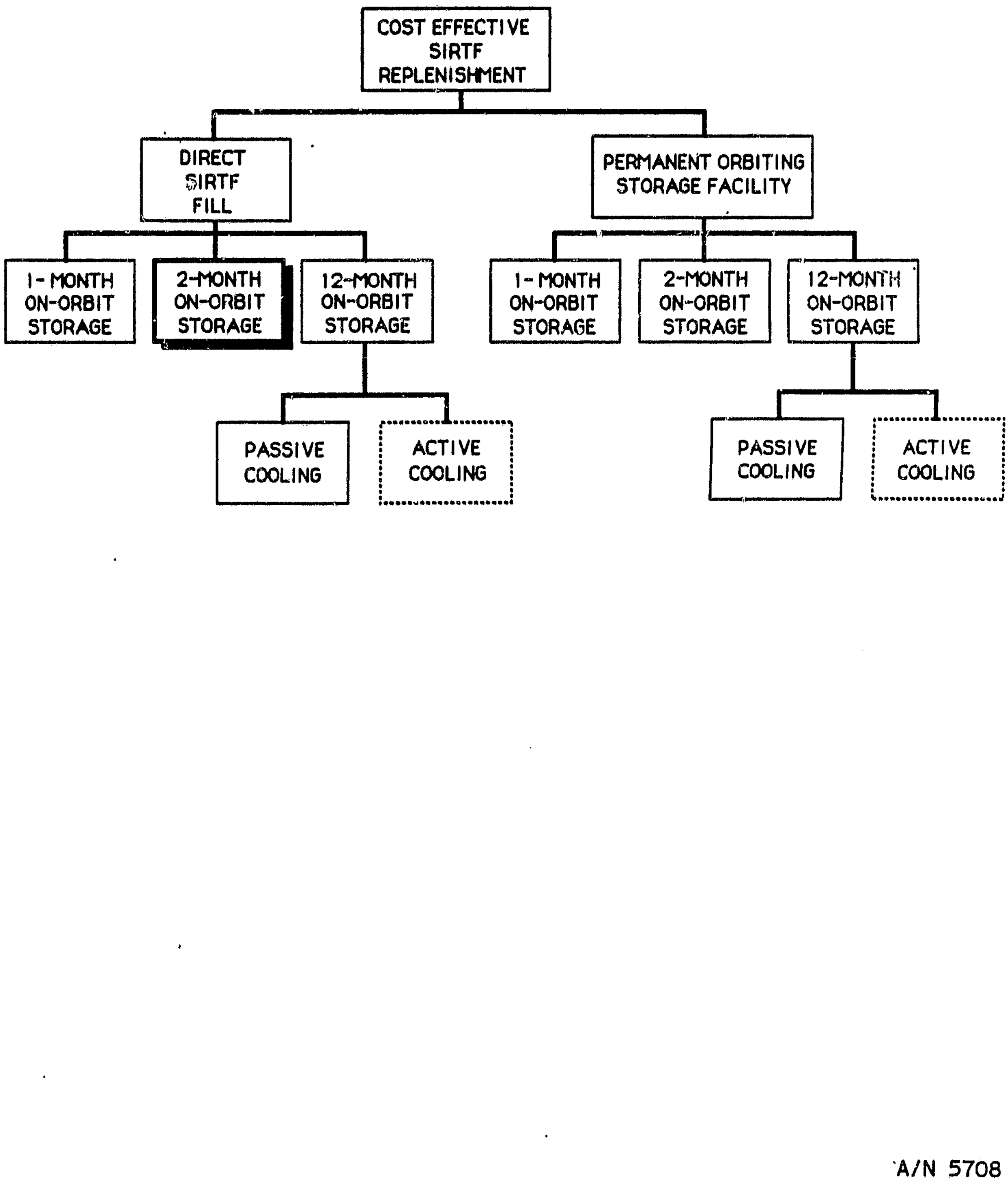

Figure 2-1 Replenishment Mission Options

Storage of one or two months on orbit has little impact on the total helium volume required, because of the low boil-off rate of a well-designed dewar. Storage of a year or more would result in a significant helium loss if the passive cooling technology of IRAS and COBE were used, and would therefore require 84 percent greater volume, with attendant construction and launch cost penalties. This could be avoided by using closed-cycle mechanical refrigeration to intercept the heat leak into the dewar, but only at the expense of refrigerator development costs and reliability risk.

For purposes of this study, we have therefore chosen to baseline an ASE that is filled on the ground and is designed to hold helium for 60 days on orbit (plus a 30 day margin). We explore the use of this ASE to service other payloads, but have not allowed the tradeoffs to be driven by that possibility.

Another intriguing possibility is to design a dewar, or family of dewars, for use with more than one cryogen. This would entail trading the inevitable performance compromises against the system-level logistic benefits of "generic" cryogen replenishment hardware, whose development costs would be shared by many potential payloads. The results of some exploratory calculations are given below.

2.1.2 Replenishment Technique Options

The choice of the liquid helium transfer technique is guided by the decision tree shown in Figure 2-2. The top-level choice between transferring He I or He II, or replacing the empty liquid helium tank with a full one, is addressed before going on to the choice of the liquid transfer technique itself. The state in which the helium is supplied to the transfer process (He I, He II, or supercritical) will probably be the one in which it is transported to space, but could conceivably be otherwise. The two most likely replenishment techniques, using either a thermomechanical pump or a centrifugal mechanical pump to transfer He II, are highlighted.

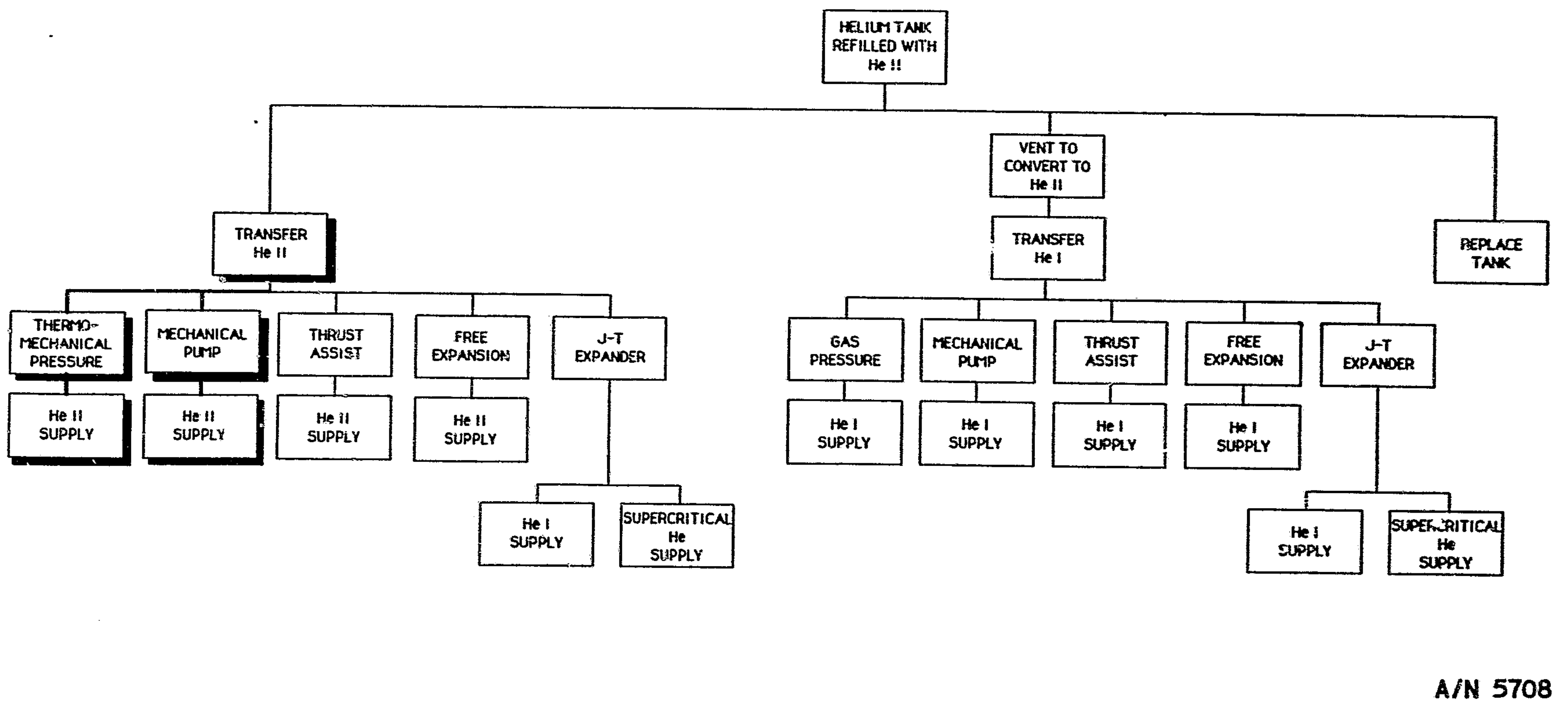

Figure 2-2 Helium Replenishment Technique Options

In this report, we will use the standard notation He I for "normal" liquid helium above the lambda-point transition at 2.18 K shown in Figure 2-3, and He II for superfluid helium below the lambda point. This will prevent confusion when discussing the two-fluid theory of He II in which it is represented as a mixture of "normal" and "superfluid" components. Supercritical helium is the dense but compressible state that occurs at temperatures and pressures higher than the critical point.

Transfer Medium

Because the SIRTF dewar operates near 1.8 K, the helium transferred into it must be cooled to that temperature before astronomical measurements can resume. This is done by venting the SIRTF dewar to space, so heat is carried off by the boiling of the helium as the pressure of the vapor above it is reduced. The higher the initial liquid temperature after transfer, the greater the loss of liquid helium in cooling it to the operating temperature.

The impact on the SIRTF mission lifetime after replenishment is seen in Figure 2-4, in which the volume lost is shown as a function of final operating temperature for various resupply temperatures. (The volume loss is more relevant than mass loss, because the empty volume represents He II at the operating temperature that might have been loaded into the dewar, but wasn't.) The huge specific heat of helium at the lambda point results in a significant lifetime advantage in replenishing with He II rather than He I. For example, filling SIRTF with 2.7 K He I would give 85% of the maximum lifetime, while filling with 2.0 K He II would give 97 percent. Filling SIRTF directly with He II at 1.8 K (or below) would, of course, give the maximum mission lifetime permitted by the SIRTF dewar.

The possible option of replacing the empty SIRTF He II tank with a full one would eliminate the need for a technique for transferring liquid helium from one tank to another in zero gravity. It would require, however, redesigning SIRTF from the ground up, with a probable penalty in dewar lifetime due to a

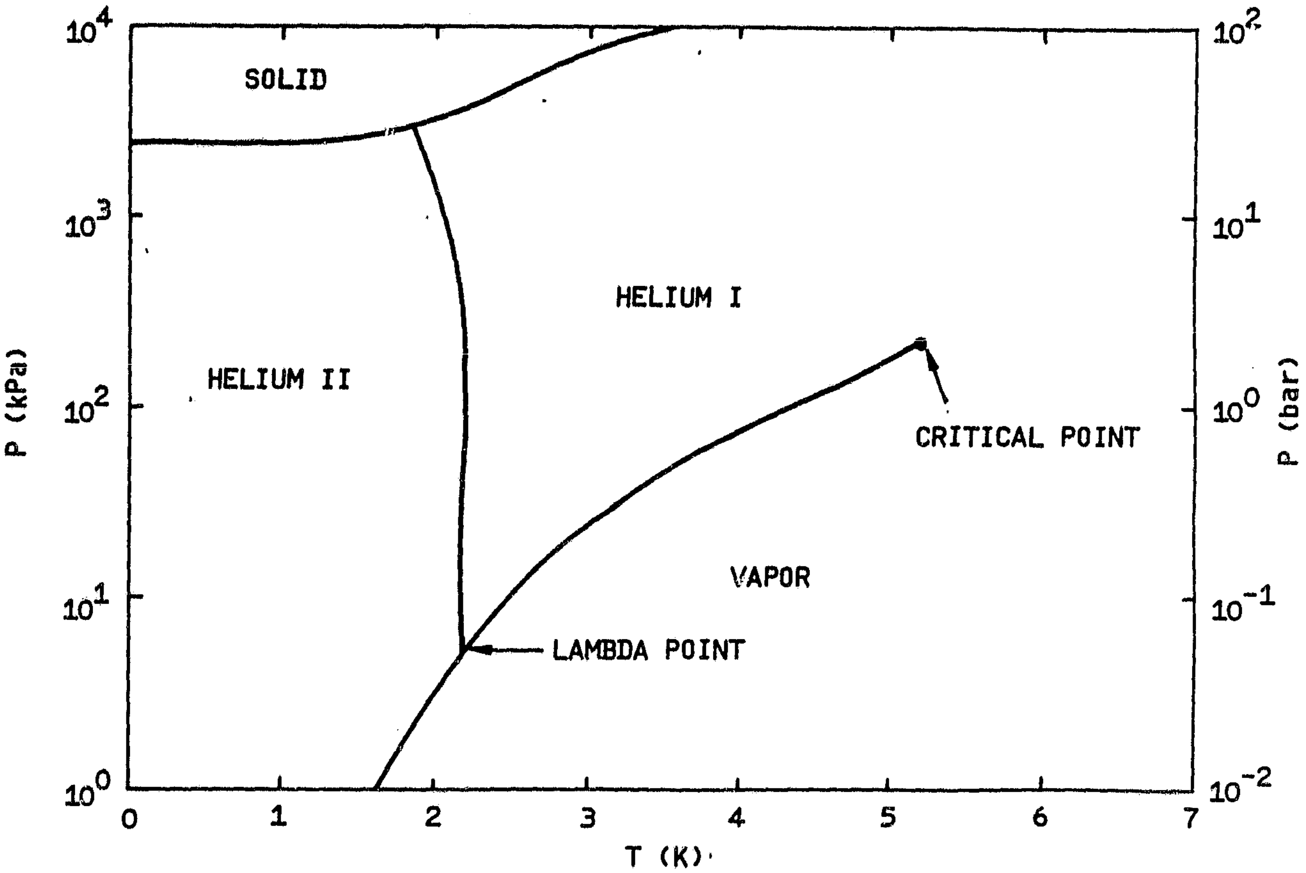

Figure 2-3 Phase Diagram for Helium

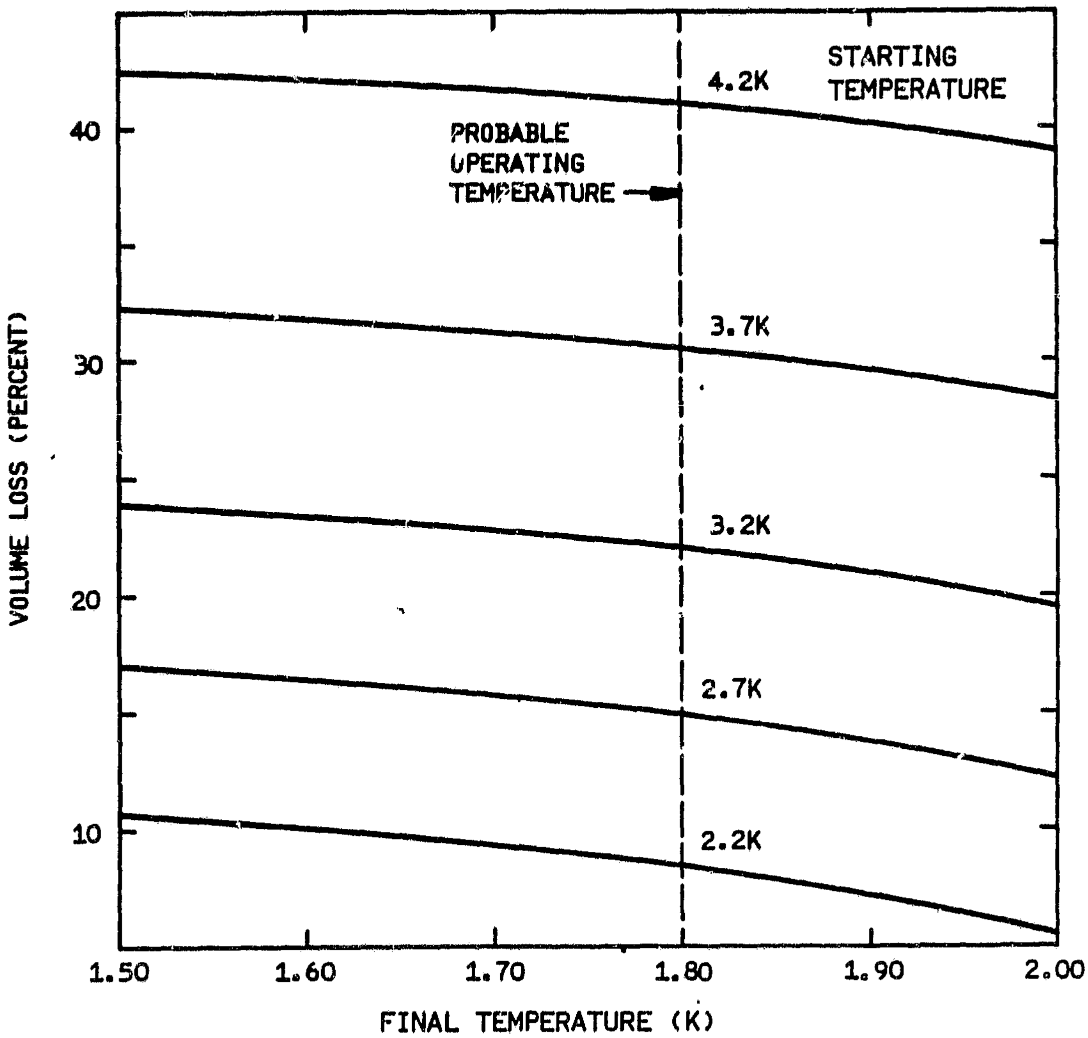

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Figure 2-4 Volume Loss In Cooling SIRTF after Transfer

degraded surface-to-volume ratio, and reliance on dematable He II joints over the multi-year SIRTF lifetime. The drastic alteration to the SIRTF design to accommodate a plug-in helium tank would also increase SIRTF mission risk by eliminating the design heritage and the benefit of flight experience from IRAS and COBE.

This tradeoff is therefore concerned permanently with the lifetime of the SIRTF dewar after replenishment. Table 2-2 shows that transferring He II directly into SIRTF at near the final operating temperature is clearly to be preferred. This produces the maximum possible lifetime, and permits the Airborne Support Equipment dewar to use the flight-proven IRAS and COBE He II technology. The only reason to consider transferring He I would be if a suitable liquid transfer technique for He II could not be found. The following paragraphs show that two promising candidates are available.

Liquid Transfer Technique

Figure 2-2 shows 5 techniques available for transferring He II. Sufficient data and experience already exists to suggest that the two highlighted are adequate to the task, and we find that the choice between them will have little impact at the overall system level. We therefore recommend that these two be developed in parallel while cryogen replenishment as a whole is developed, and that the final choice be made before committing to the final replenishment hardware design.

The thermomechanical pump relies on the unique physical properties of He II, and is therefore largely unfamiliar. It consists of a porous plug and a heater, and therefore offers the advantages of simplicity and reliability. Development efforts aimed at on-orbit transfer of He II using this technique are currently under way at GSFC[2] and at BASD. The next section discusses this option in more detail.

Table 2-2

TRANSFER MEDIUM TRADEOFF

TRANSFER MEDIUM	SIRTF LIFETIME IMPACT	OTHER IMPACTS
He II	Less than 3 percent shrinkage if filled at 2K or lower.	Requires He II containment. Can be based on IRAS, COBE experience with porous plug.
	Offers possibility of maximum life with 100% fill at operating temperature, no shrinkage.	
He I	8.4% to 40% lifetime loss due to shrinkage in cooling to 1.8 K.	Requires He I contain- with porous plug. Based on MSFC SL-2 experience.
Tank Replacement	Unknown. Requires new design, analysis.	Cost and mission risk due to loss of IRAS and COBE heritage.

Mechanical pumps, such as conventional centrifugal pumps, are an obvious and familiar possibility. These have been demonstrated by NBS with both He I and He II[3], and detailed performance measurements have been made with He I.[4] The heat input to the helium is less than that of a thermomechanical pump operated above 1.5K,[5] so the helium mass loss is lower. The biggest disadvantage to the mechanical pump is its reliance on ball bearings operating in He II, which produces reliability uncertainties. These pumps are currently under development and study by ARC/NBS.

Thrust assist, using the small aerodynamic drag on the Shuttle Orbiter,[6] special maneuvers of the Orbiter, or a long tether[7] between the supply dewar and SIRTF to produce an artificial gravity, would eliminate the need for a pump, but would constitute a major impact on the Shuttle mission. Flow rates are expected to be extremely low. Because of the low density of He II and practical limitations on the acceleration achievable, this technique can only produce low pressures, which may seriously impact cooldown of the warm transfer line, and possibly of a warm SIRTF.

Free expansion from the supply dewar to an initially evacuated SIRTF is another possibility. This is the "thermodynamic" transfer technique under study by Martin Marietta for Lewis Research Center for the Cryogenic Fluid Management Facility[8] (CFMF). The receiver tank is vented to space, valved off, and then filled with a controlled amount of cryogen from the supply tank, with the receiver vent closed. The liquid flashes to vapor in the tank and warm transfer line, absorbing heat until it is in equilibrium with the wall. The cycle is repeated until the receiver dewar is cold enough to permit filling without venting. Analysis has shown that reasonable cooldown and transfer times are possible for liquid hydrogen at more than one atmosphere, but calculations taking into account the lower heat of vaporization and pressure (maximum of 38 torr) for He II are needed to evaluate the achievable mass efficiency. Since this technique was developed primarily to avoid the use of phase-separating vents, the availability of porous plug vents for He II removes the strongest motivators for using it.

Expanding supercritical helium through a Joule-Thomson valve or orifice produces a two-phase mixture of gas and liquid colder than the supply dewar. This could, in principle, be used to produce He II to fill SIRTF, but its mass efficiency of about 30 percent rules it out as the primary transfer technique. It could be used, however, in conjunction with free expansion to remove the heat of condensation from the receiver dewar,[8] or as an auxiliary refrigerator to intercept heat leaks in the transfer line or bayonet joints. The modeling results discussed below show, however, that these heat leaks are not a large enough driver on the overall system to justify the separate supercritical helium or He I tank required.

Table 2-3 summarizes the comparison of these 5 liquid transfer techniques, and shows why we have selected the thermomechanical and centrifugal pumps for this study. From an overall system point of view, the tradeoff is between the simplicity, reliability, and high achievable static pressure of the thermomechanical pump; and the possible pressure and helium mass advantage of the mechanical pump.

Because the choice has only minor effect on the other elements of the replenishment system, we recommend that both pumping techniques be developed in parallel, and that the choice be finalized at the start of the hardware program. The performance of the two is sufficiently similar that system-level planning and tradeoffs will be valid for either one, and the two-path development approach minimizes programmatic risk.

2.1.3 Thermomechanical Pumping Technique

This section will discuss the physics, hardware implementation, and expected performance of the thermomechanical pump. Because it is usable only in He II, it is unfamiliar to most people concerned with space hardware. The physics involved and the hardware required, however, are simple, and appear to be remarkably convenient for replenishing He II cryogenic systems in space.

Table 2-3
LIQUID TRANSFER TECHNIQUE TRADEOFF

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Thermomechanical Pump	Simplicity, reliability due to no moving parts.	4.7% mass loss at 1.8 K
	Mass loss occurs in ASE dewar, so high-flow vent not needed in SIRTF.	Requires large vent in supply dewar.
	Easy to control flow rate.	Works with He II only.
	Static pressures up to 500 torr attainable.	
	Under development by GSFC, BASD.	
Mechanical Pump	Mass loss less than thermo-mechanical pump above 1.5 K	Reliability risk due to cold bearings.
	Familiar technology.	
	Works with He I, other cryogens.	
	Under development by NBS/ARC.	
Thrust Assist	No pump required.	Major impact on Shuttle/ Space Station operations.
		Low flow rates.
		Limited pressure available for cooldown.
Free Expansion	No pump required.	Driving pressure <38 torr may impede cool-down.
	May be used for other cryogens on Space Station.	
	Under development by LeRC.	Unknown mass efficiency.
Joule-Thomson Expansion	Intercept heat leak or remove heat from receiver dewar. Used in combination with another transfer technique.	Requires second dewar for supercritical He or He I. Subject to clogging of single small orifice.

After identifying the thermomechanical pump as one of the two leading candidates for replenishing SIRTF, we focused our efforts on it for two reasons: to complement the work under way at ARC and NBS on the centrifugal pump, and to provide specific focus for in-depth analysis that is largely applicable to systems employing either technique.

Physical Concept and Hardware

The thermomechanical pump is based on the "fountain effect" shown in Figure 2-5, a phenomenon which was first observed in He II in 1938.[9] A small heater was observed to cause He II to flow through the tiny pores in a plug of tightly packed powder, producing either a substantial increase in pressure above that of the bath, or to shoot a stream of liquid as shown in Figure 2-5.

The physical basis of the fountain effect can be understood in terms of the two-component theory of He II[10] which views He II as consisting of the sum of two fluids, a "normal" component with density ρ_N and a "superfluid" component with density ρ_S, such that the total He II density is given by

$$\rho(T) = \rho_N(T) + \rho_S(T). \tag{2.1}$$

The fraction ρ_S/ρ of the He II in the superfluid state depends strongly on temperature T as shown in Figure 2-6. Just below the lambda point, the liquid consists almost entirely of the normal component; as the temperature approaches absolute zero, it becomes almost totally superfluid. The normal component behaves like any other liquid, having finite viscosity and carrying thermal energy. The superfluid component carries no thermal energy (i.e. it has zero entropy), and has zero viscosity under certain circumstances. In very small channels and at sufficiently low velocities (e.g. in the pores of the porous plug) the viscosity is zero, but when flowing in larger channels (e.g. in the transfer line) a "mutual friction" with the normal component leads to viscous pressure drop.

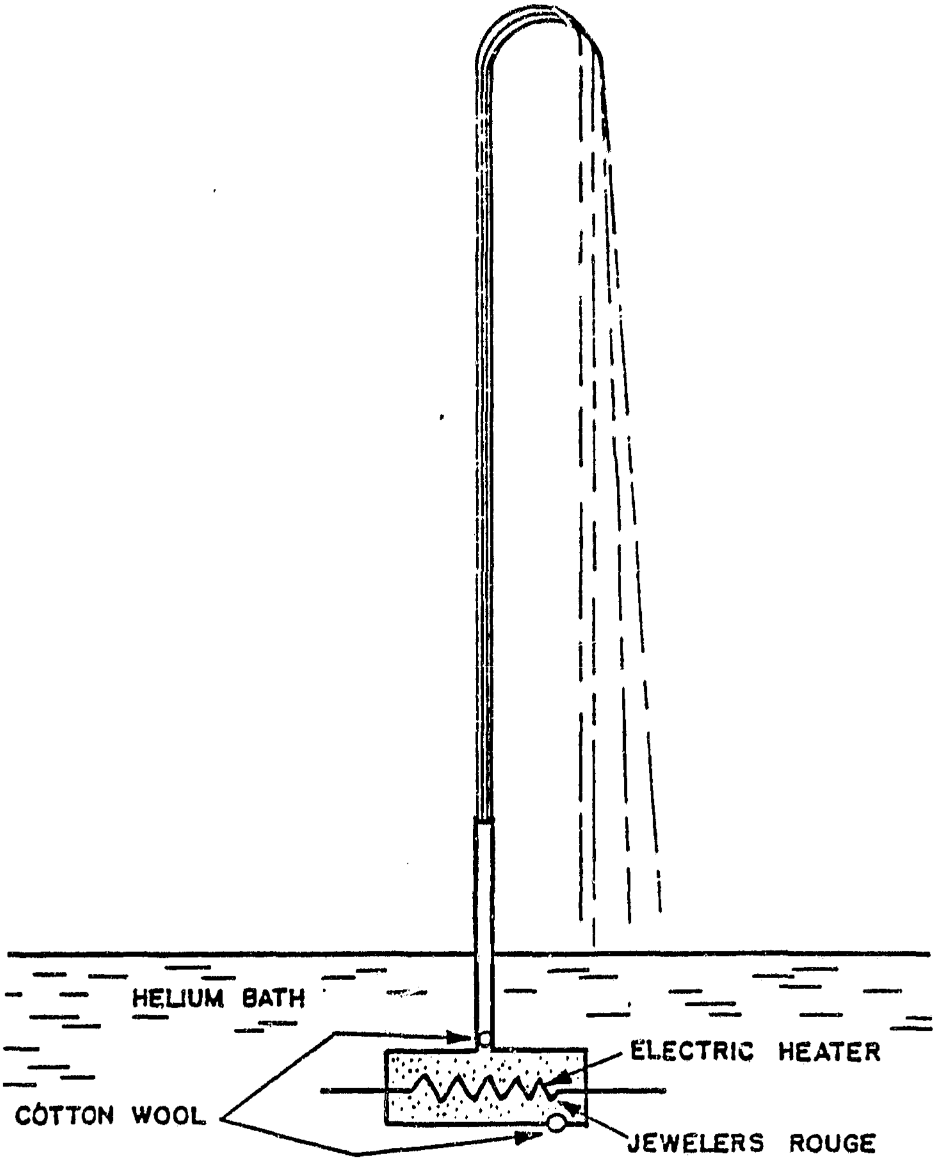

Figure 2-5 Fountain Effect in He II

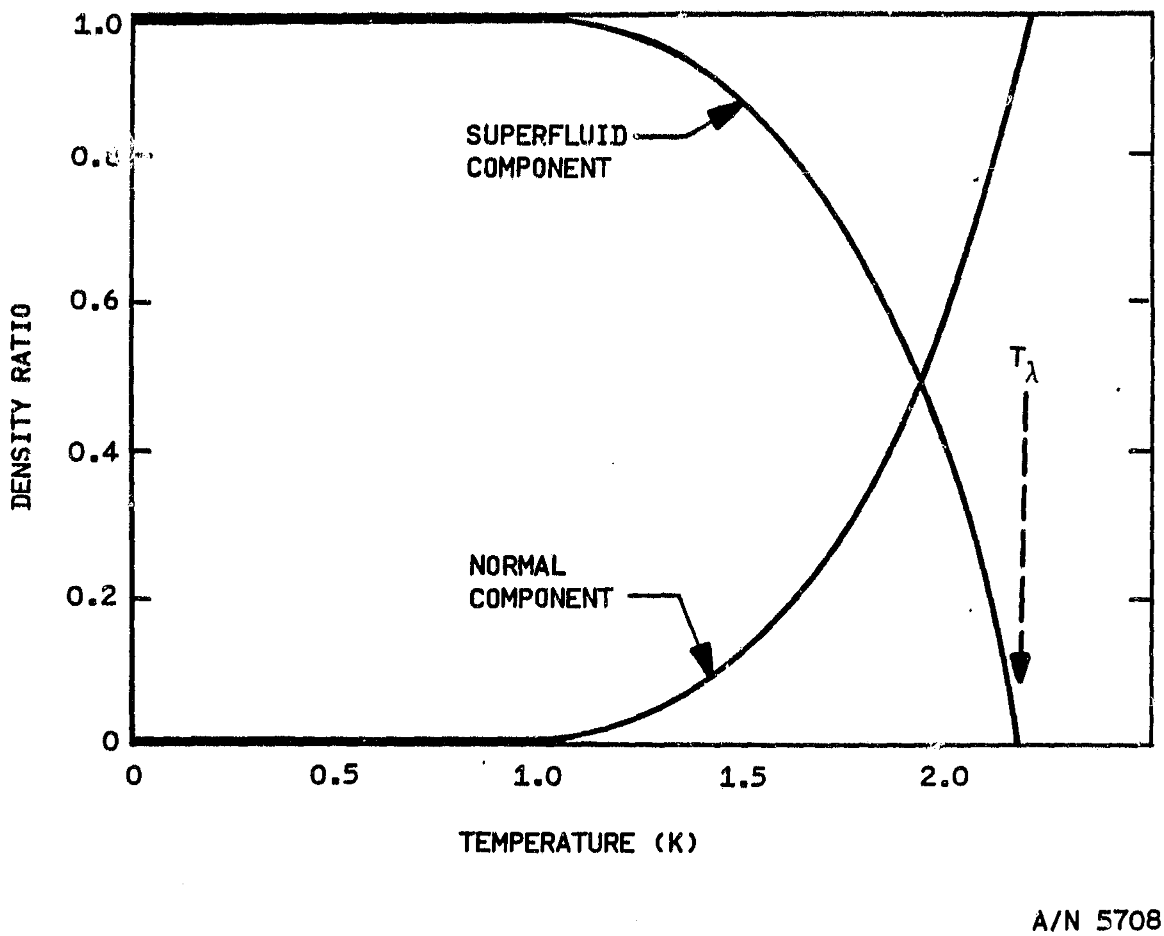

Figure 2-6 Two Components of He II

The basic operation of the thermomechanical pump is illustrated in Figure 2-7. The channel carrying He II is blocked by a porous plug, having a pore size (less than 1 μm) small enough that the viscous normal component can flow only very slowly, but the superfluid component can flow freely. An electrical heater (or other heat source, such as heat leaks into the transfer line) raises the temperature to the right of the plug, thereby reducing ρ_S below that on the left. Random thermal motion of the atoms causes helium to try to pass through the plug from both sides, but the larger ρ_S on the left permits a larger fraction of the liquid to pass freely from the left to right than the other way round. The net effect is a net mass flow from the colder side to the warmer right side, or an osmotic pressure increase ΔP on the right given by the London equation[11]

$$\Delta P = \rho S \Delta T, \tag{2.2}$$

where S(T) is the entropy of the liquid and ΔT is the temperature difference.

Extensive experimental work has confirmed that this phenomenon behaves as expected. Figure 2-8 shows that the measurements of Hammel and Keller[12] fall very close to the prediction of eq. 2.2 (suitably integrated over the finite temperature difference across the plug), and show that pumping pressures of about 500 torr can be achieved.

Figure 2-9 shows the elements of a replenishment system using a thermomechanical pump. The supply and receiver dewars are connected by a transfer line having one or two bayonet connections, and probably having a significant heat leak. The pump is connected directly to the supply dewar. Both dewars are vented through porous plug vents of the type used successfully on IRAS, and soon to be launched on COBE and on the SpaceLab 2 Infrared Telescope (IRT) and Properties of Superfluid Helium experiments.

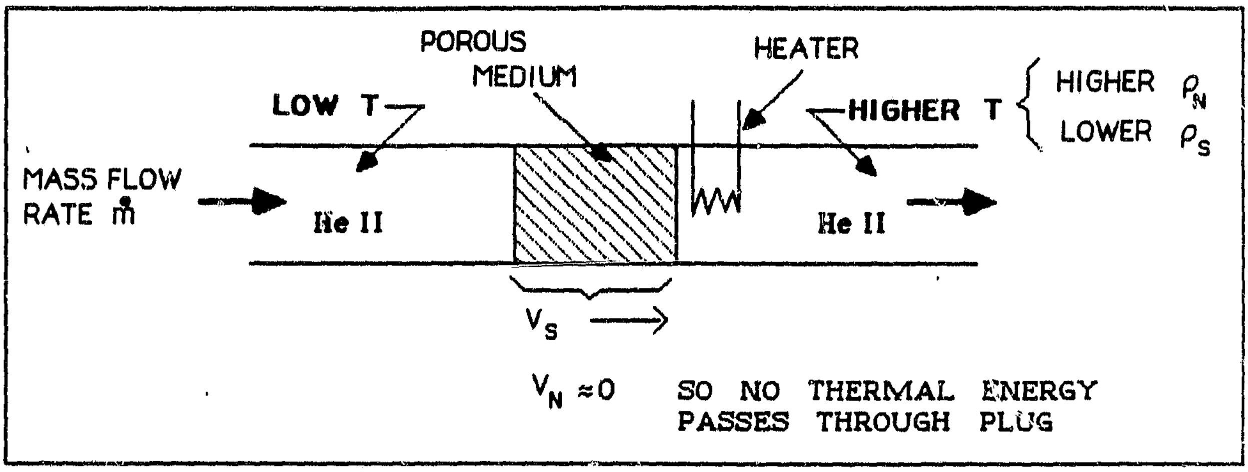

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Figure 2-7 Operation of Thermomechanical Pump

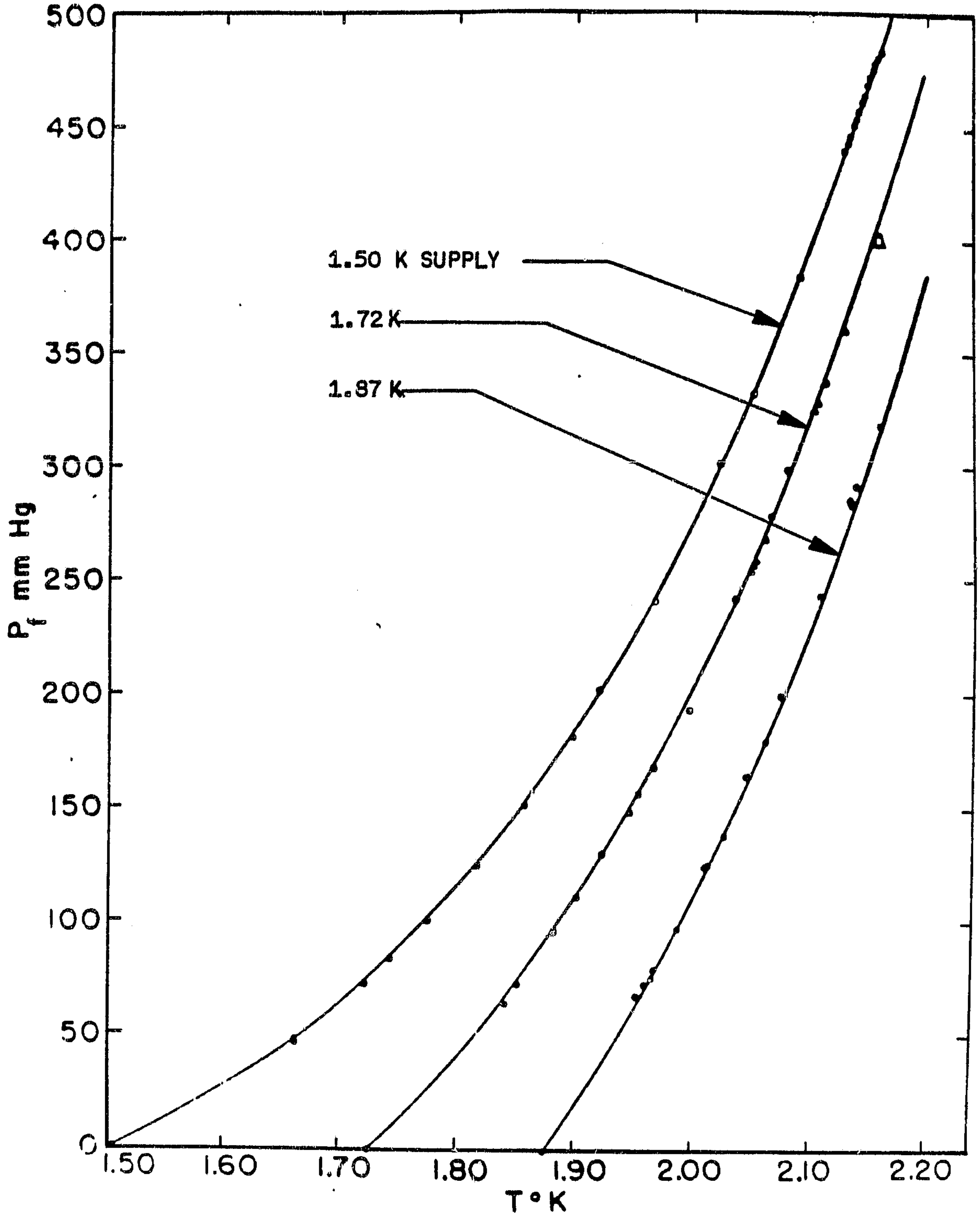

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Figure 2-8 Pressures Observed in Fountain Effect

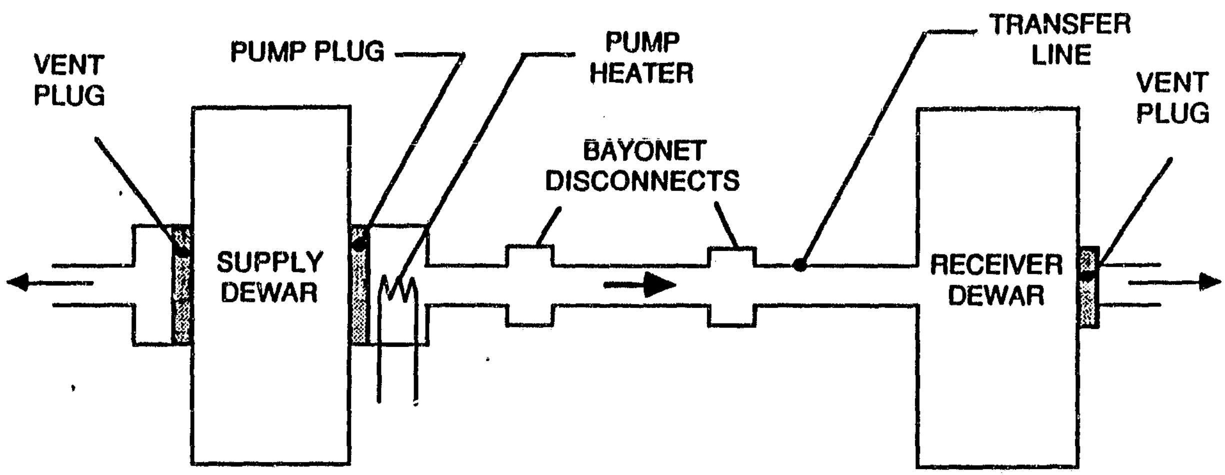

Figure 2-9 Replenishment System Based on Thermomechanical Pump

The power supplied to the thermomechanical pump inevitably boils off helium liquid, but in a way that is at first surprising. Because essentially all of the mass flow through the porous plug consists of the superfluid component which carries zero entropy, flow with zero heater power would increase the He II mass on the right without increasing its total entropy. This would result in cooling of the receiver dewar (thereby reducing ΔT and tending to stop the flow). In order to hold the temperature on the downstream side constant and maintain a steady state flow $\dot{m}$, power P given by

$$P = \dot{m} \, S \, T \tag{2.3}$$

must be supplied. This power does not cause boiling in the receiver dewar, but adds enough entropy to the pure superfluid emerging from the plug to maintain the ρ_S/ρ_N ratio appropriate to the receiver temperature

$$T_R = T_S + \Delta T, \tag{2.4}$$

where T_R and T_S are the temperatures of the receiver and supply, respectively. Another way to look at it is that this is the power required to warm the 100 percent superfluid component from absolute zero to T_R.

Since the mass being extracted from the supply dewar is essentially all superfluid component, the total entropy on the left is constant while its mass is being reduced. This would result in the warming of the supply dewar (again, reducing ΔT and tending to shut off the flow) unless heat is somehow extracted. For steady-state flow, T_S is held constant by boiling in the supply dewar, with the pump power P producing a vapor flow $\dot{m}_{LOSS}$ out the supply dewar vent.

This mass loss is inherent in the use of the thermomechanical pump, and is part of the system-level tradeoff to select the transfer technique. The mass loss fraction is given by

$$\dot{m}_{LOSS} / \dot{m} = P / L$$
$$= S\,T / L\ , \qquad (2.5)$$

where L is the latent heat of vaporization. This fraction is a function of the temperature and fluid properties alone, and does not depend on hardware design or transfer rate. Figure 2-10 shows that the transfer efficiency is improved by reducing the temperature, and that the mass loss is less than 5 percent for transfers at 1.8 K or lower. This would require a supply dewar 5 percent larger than required for an ideal transfer. This may be an acceptable penalty to pay for the inherent simplicity of the thermomechanical pump.

Expected Performance

In order to learn what sort of performance can be realistically expected from the thermomechanical transfer technique, BASD has undertaken an internally funded program of experimental and theoretical work on the problem. Small scale laboratory tests have confirmed the underlying theory, and have shown that 100 percent filling of the receiver dewar is possible. We have developed a detailed numerical simulation which is revealing the design drivers and allowing us to predict overall system performance under various conditions. Large scale laboratory tests are underway to verify the simulation results, and to demonstrate this technique on a scale relevant to replenishing SIRTF.

Appendix B discusses the model we have developed, and gives the most important results obtained to date. We will summarize these results here, and discuss their implications for the conclusions of this study.

Figure 2-11 shows the hardware configuration presently modeled. The line linking the dewars is taken to be 6 m long, 2.54 cm in diameter, and have 0.2 W/m of heat leak along its entire length. (Actually, the heat leak in the 4 m inside the two dewars will probably be much smaller.) Each of the

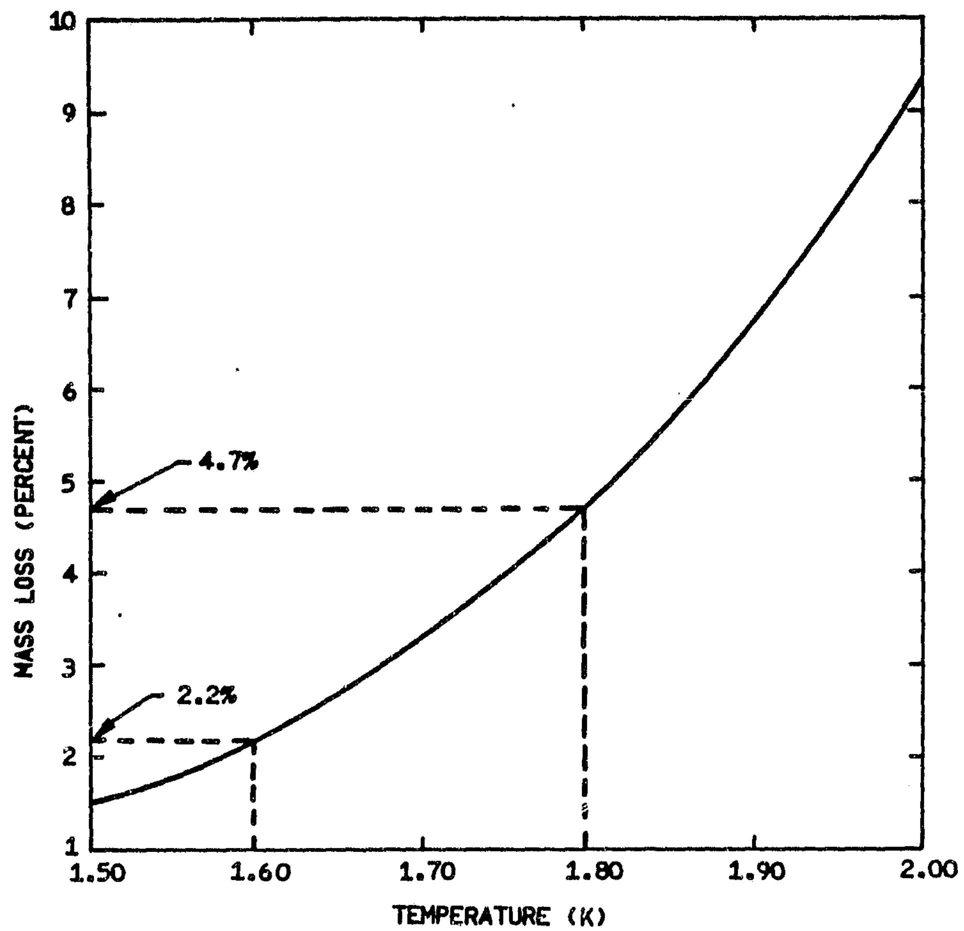

Figure 2-10 Mass Loss With Thermomechanical Pumping

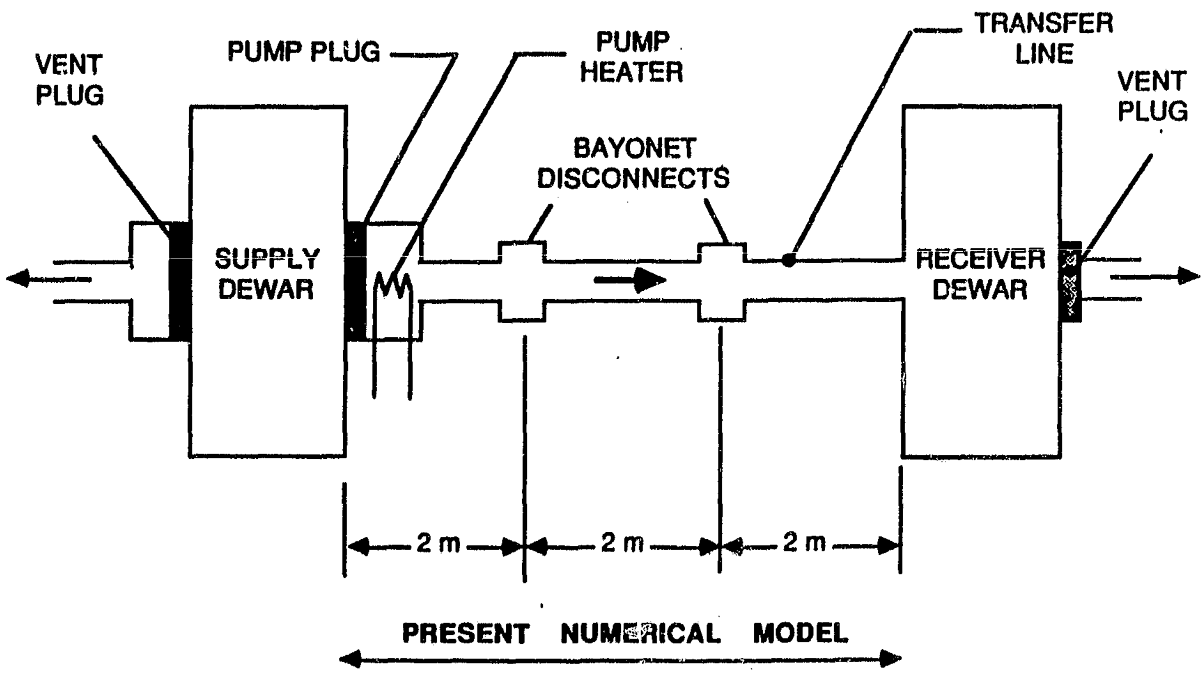

Figure 2-11 Hardware Configuration Modeled

two bayonet couplings are assumed to contribute 1 W of heat leak. The supply and receiver dewars act as constant-temperature reservoirs during the steady-state transfer.

The thermodynamic path on the P-T diagram followed by the liquid is shown in Figure 2-12 for one particular set of conditions. The liquid in the supply dewar is brought from its equilibrium vapor pressure at T_S to a substantially higher pressure, given by eq. 2.2. The liquid then flows down the transfer line toward the lower pressure in the supply dewar (the vapor pressure of He II at T_R), increasing in temperature until it reaches the receiver at T_R.

Expected performance for two different supply temperatures is shown in Table 2-4. The principal difference is the increase in mass transfer efficiency at the lower temperature, from 95.3 percent to 97.8 percent, due to the decrease in mass loss shown in Figure 2-10. In either case, the fluid is transferred into SIRTF at a temperature less than 0.06 K above that of the supply dewar.

Most of the laboratory work with He II to date has been with flow rates and geometries such that the flow of the superfluid component is laminar, even though the normal component may be turbulent. Under these conditions, the thermal conductivity along the column of moving liquid is remarkably high, permitting a substantial fraction of the heat leak into the transfer line to flow upstream and add to the heater power in driving the mass flow, according to eq. 2.3.

There is uncertainty as to precisely what happens when the flow of the superfluid component is highly turbulent, as may be the case in the conditions relevant here. There is some evidence[13] that the two components become locked together, effectively eliminating the anomalous thermal conductivity along the liquid column. To test the sensitivity of the performance of the thermomechanical transfer to this possibility, we have modeled two limiting cases:

Table 2-4
PERFORMANCE AT TWO TEMPERATURES

	SUPPLY TEMPERATURE	
PARAMETER	1.6 K	1.8 K
Electrical Heater Power	19.34 W	40.49 W
ΔT at pump	0.012 K	0.007 K
ΔP at pump	3.99 torr	4.18 torr
ΔP across transfer line	2.43 torr	2.66 torr
Receiver dewar temperature	1.658 K	1.833 K

1000 liters/hour flow, 2.54 cm line diameter, turbulent limit model.

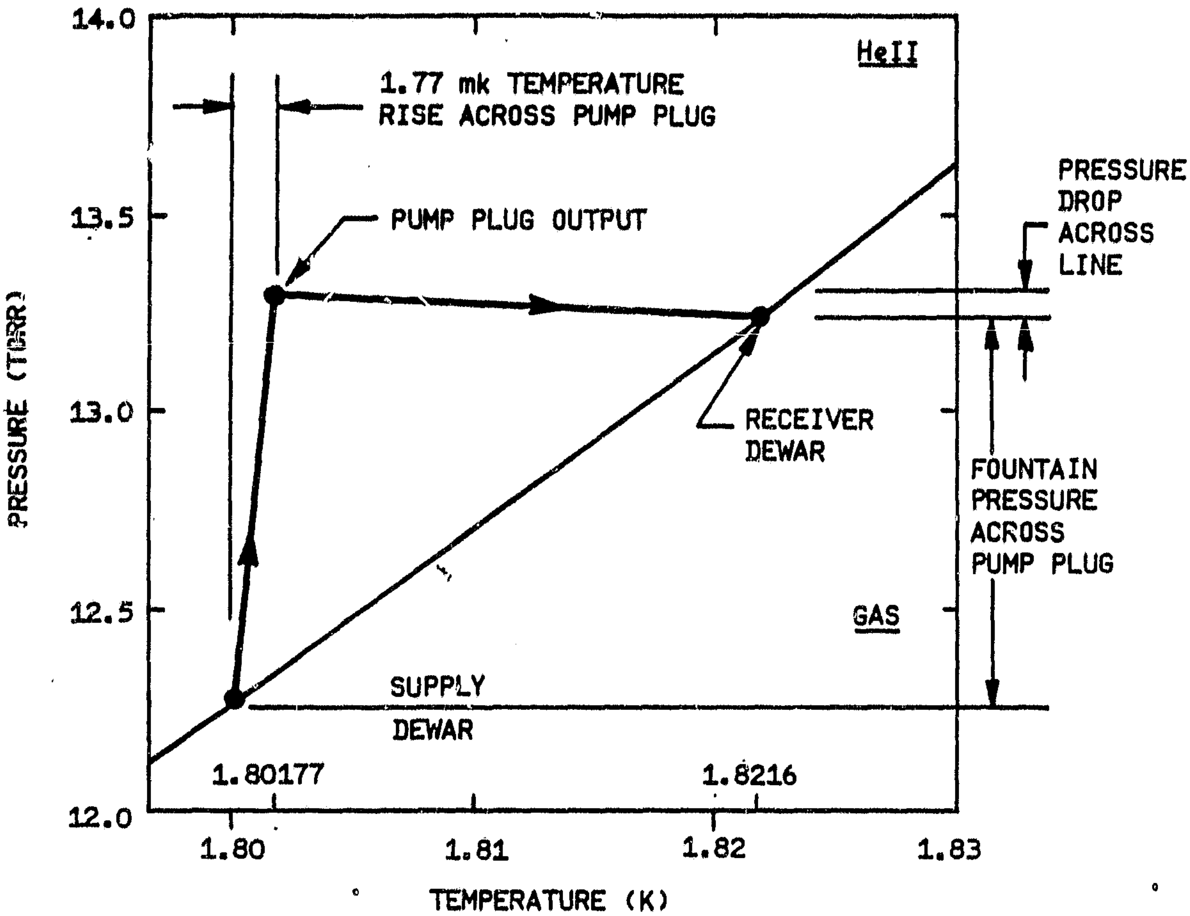

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Figure 2-12 Thermodynamic Path of Thermomechanical Transfer for 1.27 cm Line, Laminar Flow

- Laminar flow, with pressure drop given by the laminar flow equation, and high thermal conductivity; and

- Turbulent limit, with pressure drop given by the Blasius equation, and thermal conductivity along liquid column negligible compared to forced convection.

These two cases produce qualitatively different temperature profiles along the transfer line, as shown in Figure 2-13. (In this figure, a 1.27 cm diameter line is used to produce larger, more easily seen temperature changes than in the 2.54 cm diameter lines baselined.) Table 2-5, however, shows that the difference in overall performance, while scientifically interesting, has little impact at the system level for transferring large quantities of He II in space.

The modeling and experimental work to date have not established the limits of this technique, but they have shown what sort of performance is possible. The conclusions that can be drawn for purposes of this study are:

- The thermomechanical transfer technique is expected to work well, with 100 percent liquid transfer into the SIRTF dewar at a temperature less than 0.1 K above that of the supply dewar, and

- Flow rates on the order of 1000 liters/hour are achievable.

At this point it is reasonable to baseline the thermomechanical transfer technique for replenishing SIRTF in space, with the centrifugal pump as an attractive backup. Careful examination of the startup transient will be necessary.

Table 2-5

PERFORMANCE BOUNDS FOR DIFFERENT HEAT TRANSFER ASSUMPTIONS

PARAMETER	HEAT TRANSFER ASSUMPTION LAMINAR FLOW	TURBULENT LIMIT
Electrical heater power	37.97 W	40.49 W
ΔT at pump	0.001 K	0.007 K
ΔP at pump	0.65 torr	4.18 torr
Receiver dewar temperature	1.813 K	1.833 K

1.800 K supply temperature, 1000 liters/hour flow, 2.54 cm line diameter

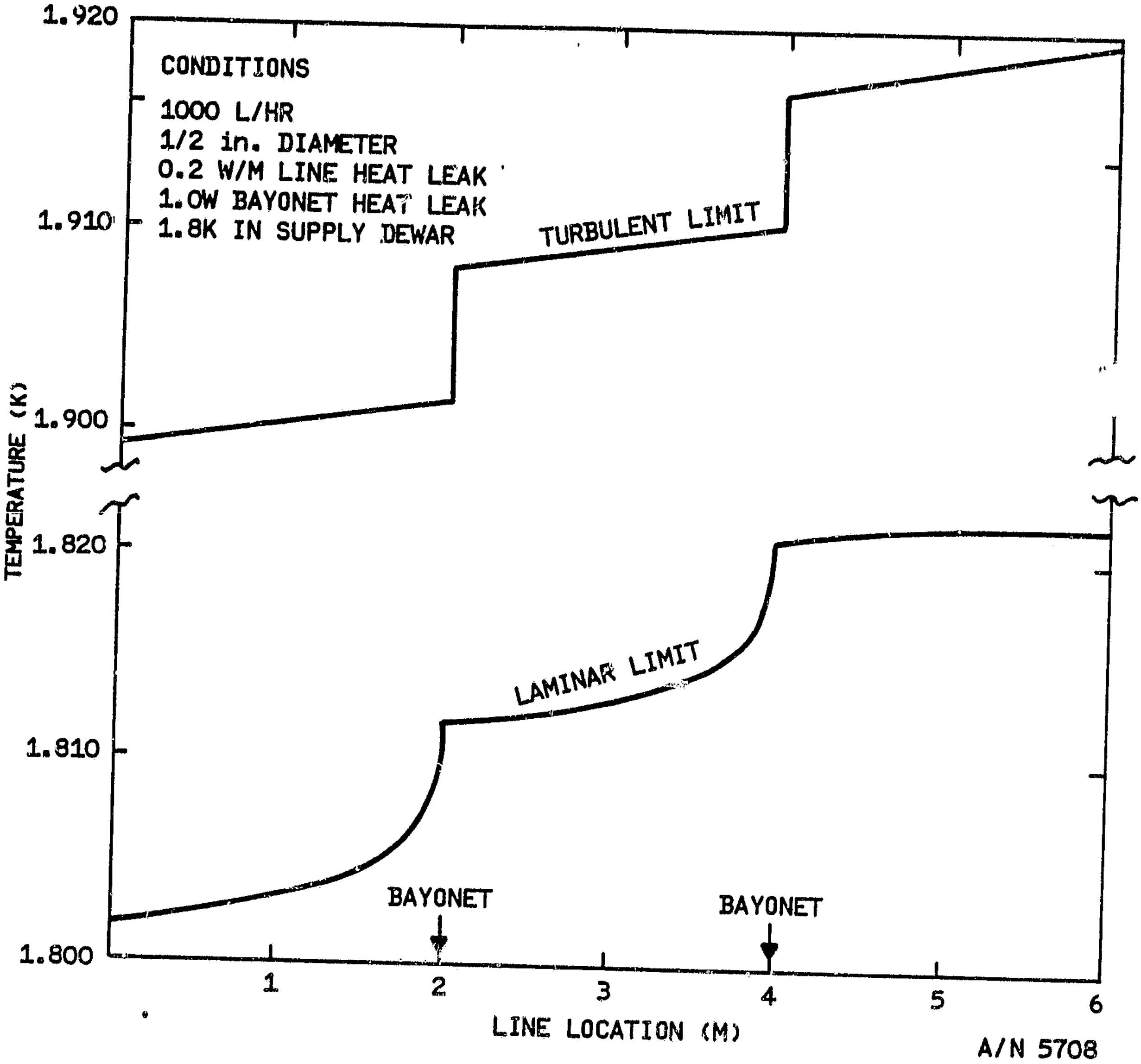

Figure 2-13 Temperature Along Transfer Line At 1000 Liters Per Hour For Different Heat Transfer Assumptions

2.2 MODIFICATIONS TO SIRTF

This section presents the recommended modifications to SIRTF required to perform an efficient on-orbit replenishment. The changes identified are directed at all phases of replenishment including cooldown, fill, stabilization, and topoff. The recommendations are a result of reviewing many facets of transfer operations such as:

- transfer operations for the IRAS project;
- cooldown performance of COBE;
- comprehensive review of conditions that might take place in accomplishing an on-orbit cryogen transfer on the Shuttle or the Space Station within a practical time frame; and
- a fluid flow model of the Helium-II fill process.

2.2.1 Impact of On-Orbit Cooldown

In filling a cryogen system the longest time element required is for the cooldown process. This is due to the large amount of heat which must be removed from the receiver tank and the instruments attached to it. In the case of SIRTF these instruments are the telescope and MIC. This heat must be removed through either GHe conduction or forced convection to the cooling GHe from the tank, and through thermal-mechanical joints of sometimes different metals, and or instrument joints that are purposefully isolated to permit elevated temperatures during flight operation. For ground operations extended cooldown time results only in a larger quantity of coolant required. In space extended cooldown time could result in not filling the receiver tank because of insufficient mission time.

Tradeoff comparisons of the three major constituents for cooldown were made and are summarized below. The three elements are:

- ability of the GHe to absorb the heat being removed from the cryogen tank, and telescope and MIC instruments;

- heat transfer coefficient between the metal thermal joints;

- heat transfer coefficient between the GHe boundary layer and the tank.

The minimum cryogen quantity is achieved by limiting the helium flow to that required to absorb the heat flow into the GHe. At the beginning of cooldown the line size limits the rate of GHe flow unless modified. The heat transfer coefficient across the thermal joint used for cooling the IRAS telescope was the limiting factor heat transfer and led to a long cooldown time (42 hours) and larger than expected consumption of LHe (2400 liters for cooldown). ("Cooldown time" as used here means the time required to begin collecting liquid. The time required for the temperature of the optics to fully stabilize is not included.) For COBE the design was changed to higher joint loadings, providing a higher thermal conductance which resulted in a cooldown time of 20 hours. The fill time was less than 5 hours. The BASD model developed for the STICCR study predicted, before the fact, a cooldown time for COBE of 29 hours. The total cryogen cooldown quantity predicted was 1240 liters; actual consumption was approximately 1190 liters. The conductance predictions between the GHe and the tank, and the metal-to-metal thermal joints were conservative.

2.2.2 Plumbing Modifications

As mentioned above certain changes are recommended to improve cooldown characteristics of the SIRTF dewar. Figure 2-14 pictorially presents the optimized flight fluid management scheme with the on-orbit replenishment changes enclosed in the dashed box. The modifications are summarized in Table 2-6.

Table 2-6
PLUMBING ADDITIONS/MODIFICATIONS
REQUIRED FOR REPLENISHMENT

Item	Function
Forced Convection Heat Exchanger	Increased GHe heat transfer reduces cooldown time
Large Porous Plug	Flexibility during transient cooldown and flexibility in replenishment fluid temperature
Short Vent Line	Increased fluid flow at warm temperatures reduces cooldown time
Increased Valve Orifice	Reduced pressure drop for precooling system

The forced convection heat exchanger has been added to enhance the heat transfer between the GHe and the tank. It is located next to the cryogen tank mounting flange to increase the conductance to both the tank and the telescope/MIC areas. As mentioned above a transient model of the cooldown of SIRTF was developed to determine the sensitivity of the various elements. Adding the forced convection heat exchanger in series with the internal tank GHe conduction cooling, the gas to metal heat exchange rate was increased to the value that it no longer is a constraint for cooldown. The GHe conductance across the 1.5 inch boundary layer caused by the internal structural fins was approximately 18.4 watts/K at 250K and decreased to approximately 1.6 watts/K at 10K. The forced convection heat exchanger can be made to transfer 107 watts/K at 250K and 60 watts/K at 10K. Analysis for these data are in Appendix D. Also liquid will collect in the tubular heat exchanger before it collects in the tank so that film or nucleate boiling will take place enhancing the cooldown process to the telescope at the cold temperatures.

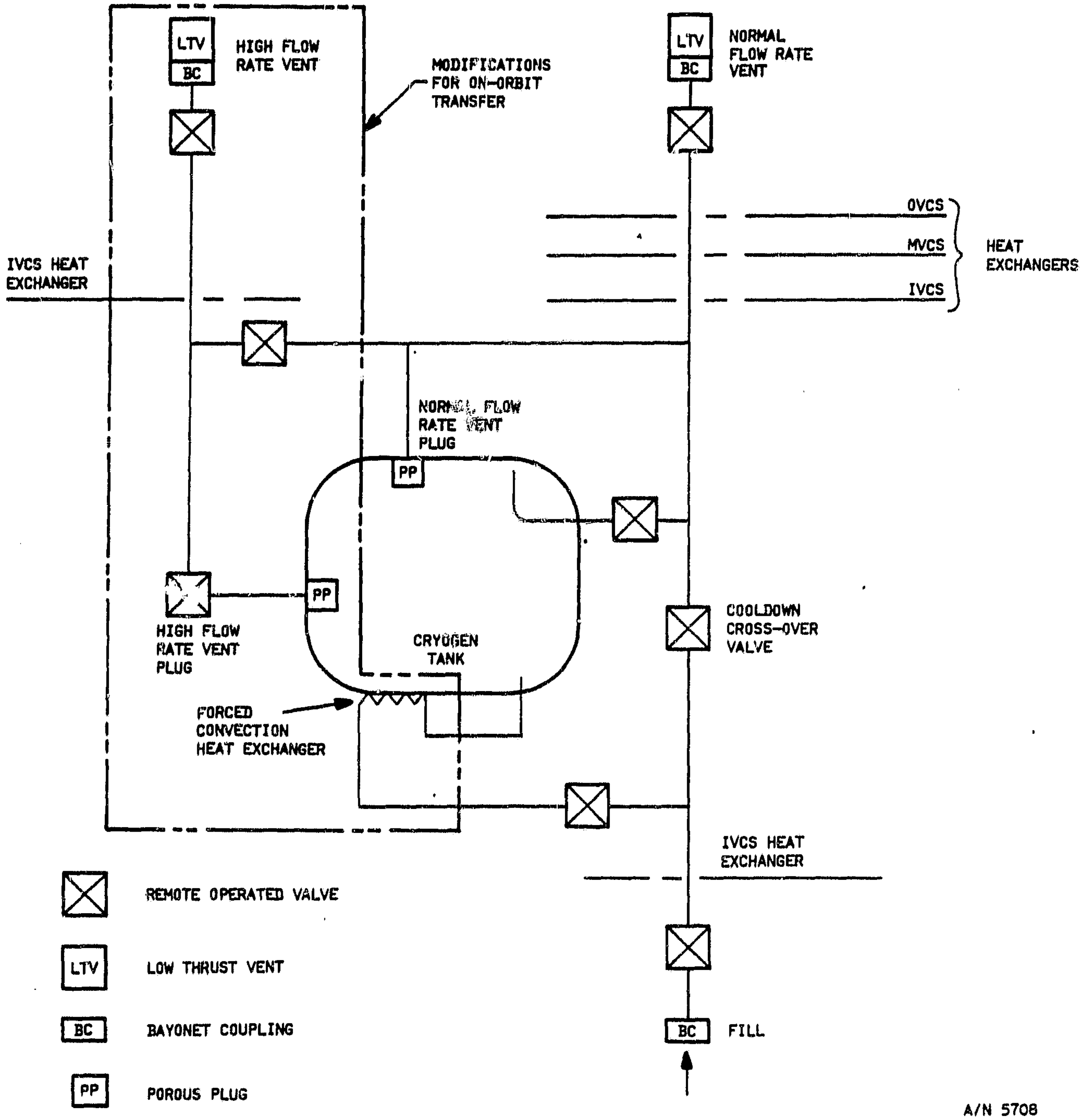

Figure 2-14 SIRTF SFHe System Modified for Replenishment

The second item added to the plumbing is a separate large vent porous plug which permits loading of SfHe at temperatures higher than normally desired for on flight operation, i.e., load at 2.0K and reduce tank pressure until tank temperature is reduced to 1.6K in a short time. This large porous plug also permits flexibility during transient cooldown operation when the incoming helium may be slightly above the lambda point and the transition to superfluid can be made to occur in the plug.

Flight cooldown will be enhanced by adding a flight cooldown valve which permits the cooldown GHe to be vented out the short vent line connected to the transfer plug. This permits the normal flight vent to still function and maintain the shields cold, but exhausts the bulk of the effluent GHe during cooldown with only a small pressure drop.

One of the main flow restrictions in any fluid management system are the valves. For IRAS ball type valves were used to minimize back pressure. Since flow conductance will be important for on-orbit replenishment, more emphasis must be placed on the valve selection and design. Ball, butterfly, or gate valves of about the same diameter as the vent lines will be rquired to permit a large flow without increasing the pressure drop across the vent and fill system.

Redundancy is a very important safety consideration. It is not clear at this time whether space station safety will permit function redundancy or require complete component redundancy. The proposed system is functionally redundant in that the tank can be vented by a number of paths; e.g., the fill line, the porous plug, the two vent lines. The flight porous plug for SFHe retention cannot be internally closed off and is protected from over pressure by an external burst disk and relief valve system.

2.2.3 Aperture Cover

In preparation for cryogen replenishment, the aperture of the SIRTF telescope will be closed to prevent contamination from entering the telescope. The planned cover would be a simple blade type shutter which does not form a vacuum seal but does eliminate line of sight paths for gas and particle contamination. This blade will be at the outer shell temperature and as such could radiate up to 13 watts of heat to the fore baffle.

The radiated heat load can be reduced by several methods: The first and simplest is to plate a low emissivity coating on the blade thereby reducing the effective emissivity; the second method is to install a blanket on both surfaces such that the radiated heat load is reduced, also the cover will cool off and thereby reduce the heat load; the last and most difficult, but most effective, is to thermally isolate the blade cover and cool it to less than 70K by GHe refrigerant flowing through a heat exchanger attached to the sliding cover.

In the recent BASD study[1] of SIRTF a case was made for a vapor cooled fore baffle. With the vapor cooled fore baffle design, very little of the cover parasitic heat actually gets to the cryogen tank, since the fore baffle is effectively isolated from the tank and the parasitic heat is carried away in the effluent GHe, less than 0.5 watts in the worst case. See Appendix D for the detailed analytical data.

2.2.4 Impact on SIRTF Performance

This section discusses impact of the on-orbit replenishment modifications on the SIRTF lifetime. The two contributors that decrease the lifetime are the increased fill line size (assumed to be 2.5 cm. in diameter instead of 1.9 cm as was used in the thermal/cryogen system study), and the additional short vent line from the transfer porous plug. The degradation is 0.18 years for the baseline 4,000 liter dewar, or a decrease from 2.59 years to 2.41 years. The backup analysis and model description is included in Appendix D. This is a reduction of 7 percent in lifetime.

A second area of degradation could be refilling a warm SIRTF after an instrument changeout. The precooling phase assumes that the total system is cold at start of fill but, is very possible that components within the instruments may not have good thermal contact and be cooling down for hours after fill. This would degrade the lifetime by some factor. To counteract this problem the timeline provides for a settling time and then a topoff. A second way of reducing long term cooldown is to require that the instruments be designed to be cooled within a certain time, and to verify this by test.

The operating temperature of SIRTF will not be impacted by an on-orbit replenishment. The joints must be designed to remain in contact after multiple thermal cycles and launch vibration and will be verified in ground test operations long before on-orbit replenishment.

2.3 AIRBORNE SUPPORT EQUIPMENT DESIGN CONCEPT

Based on the tradeoffs discussed above, we present here the design concept for the ASE for replenishing the He II in SIRTF. Operations, replenishing hydrogen, and replenishing Helium-3 are discussed later.

The fundamental design requirements that we have used in defining the ASE are that it be:

- Capable of filling SIRTF within 60 days of launch,
- Capable of being used on either the Space Shuttle or the Space Station, and
- Self-contained, consisting of one easily-handled unit (the External ASE Kit), plus the control panel (the Internal ASE Kit).

The first requirement determines the cryogenic design of the ASE and its volume. The second determines its overall configuration and the SIRTF handling hardware associated with it. The last requirement is intended to simplify operations, and amounts to requiring that the transfer line, electrical umbillicals, etc. be stowed on the large ASE dewar.

2.3.1 Cryogenic Design

This section discusses the cryogenic design drivers for the Airborne Support Equipment. Parameters of primary importance in the tradeoffs were:

- Quantity of supply cryogen required
- Conditioning required for transfer efficiency
- Liquid acquisition by the pump

Quantity of Supply Cryogen Required

The first design driver includes all elements which contribute to the quantity of LHe required to cool and fill the SIRTF receiver dewar. This includes the efficiencies for cooldown, line sizes which might limit flow rate, and conduction and convection heat transfer coefficients. A series of tradeoffs were made regarding the effect on cooldown time of increasing the heat transfer coefficient between the tank and the GHe flow, and of increasing the metallic thermal joint contact between the telescope/MIC instruments and the dewar mounting ring. The result of these tradeoffs was that the metallic conductor is the limiting factor and doubling the GHe heat transfer had little impact on the cooldown time and quantity of LHe required to precool the SIRTF cryogen tank. This is discussed in more detail in paragraph 2.4.2.

To determine the total quantity of cryogen required, the cooldown quantity was determined and added to the fill quantity based on a transfer efficiency of 95 percent (the supply dewar loss through the vent at 1.8K). Then the tank was sized for storage losses of 0.1 percent, 0.2 percent, and 0.5 percent per day. These percentages represent an IRAS type insulation with a fourth vapor cooled shield, an IRAS type system, or an insulation system representing standard commercial supply dewar technology, respectively. The results of the three different insulation systems designed to fill SIRTF when still wet, at 150K, and at 300K are presented in Figure 2-15. As can be seen the 0.1 percent per day loss system is almost mandatory, at least

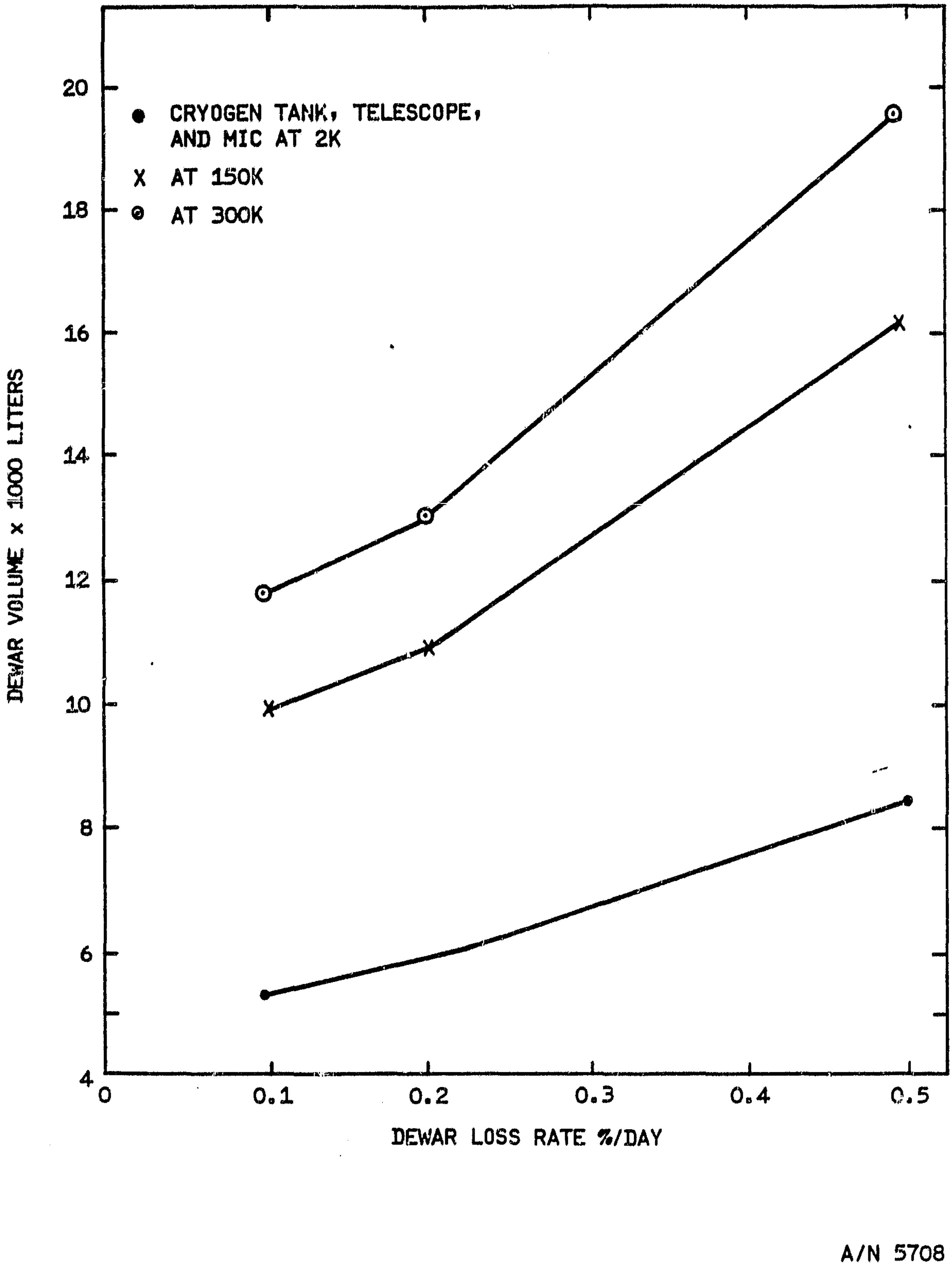

Figure 2-15 Comparison Of Supply Dewar Loss Rates

when instrument changeout takes place and the cryogen tank must be cooled from 300K. The effect of cooldown, transfer efficiency and supply dewar hold time are better appreciated in Table 2-7 which identifies the percentage each contributes to the supply dewar sizing.

Table 2-7

Contributors to Cryogen Volume Required

	SIRTF Tank Condition					
	Wet		150K		300K	
Operation	liters	%	liters	%	liters	%
Cooldown	25	0	3,545	36	5,078	43
Transfer Efficiency	210	4	210	2	210	2
Fill	4,000	75	4,000	41	4,000	34
Margin (15% of cooldown and delivered quantity)	632	12	1,163	12	1,325	12
Hold Time	458	9	882	9	1,069	9
Total	5,325	100	9,800	100	11,682	100

Supply Dewar Venting

This refers to the requirement to vent GHe from the supply dewar during the transfer to maintain the fluid at a lower temperature than the receiver dewar. The percentage loss of helium is shown in Figure 2-16. As can be seen, is a function of temperature only.

Liquid Acquisition by the Pump

Some device must be used to assure that a sufficient flow of helium is always present at the pump entrance to maintain the SfHe transfer. Two concepts considered are the use of surface tension screens or a centrifugal device that causes the liquid to be thrown to the outside surface of the

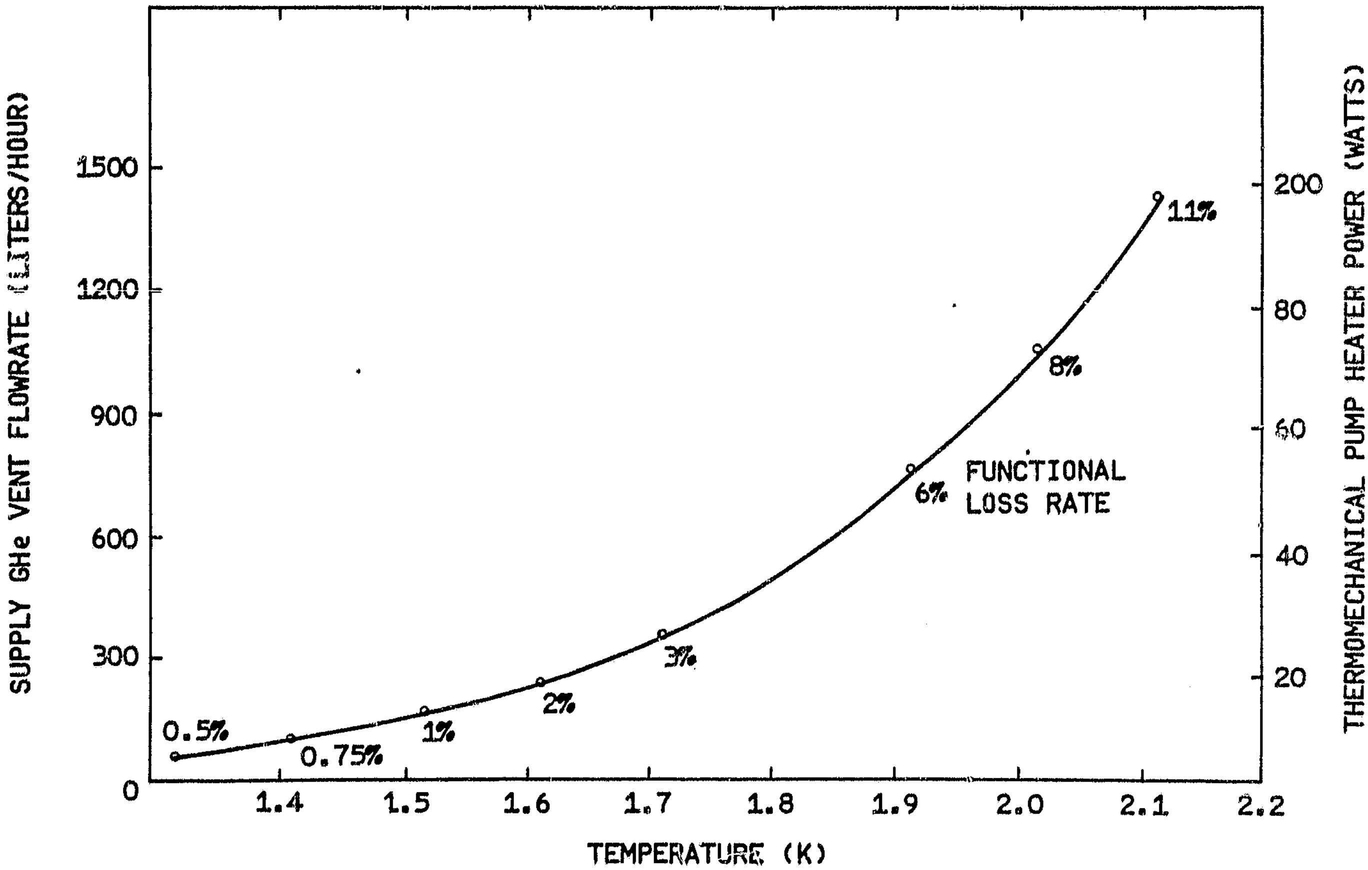

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Figure 2-16 Supply Dewar Helium Loss

tank in a swirling motion. Two types of devices which have been suggested for this action are big paddle wheel blades driven by a motor, or redirecting a small portion of the transfer helium back into the tank through tangential jets to cause swirling action. Both concepts are preliminary and deserve further study. Preliminary analysis indicates that surface tension screens presently available will probably retain the SfHe. The magnitude of orbital G-loads which may be encountered must be reviewed relative to the surface tension screen retention capability.

Fluid Management Scheme

Figure 2-17 presents one concept for a SfHe supply system which could be used to refill SIRTF on orbit. It consists of a cryogen tank connected through various fluid management components and lines to a transfer line which is either remotely or through astronaut EVA connected to the vehicle being resupplied. The transfer line will probably be of minimum length consistent with the fixturing required to hold the SIRTF near the ASE supply dewar. The schematic pictures two bayonets which are typical but to reduce heat leak to the SfHe being transferred only one may be desirable.

Included in the fluid management components are large orifice, remotely actuated valves used to control the SfHe. A fill line is included for both ground and on-orbit refill of the SfHe. The vent line is for use during ground fill. There are three porous plugs included in the supply dewar. The first is a small size plug, sized for venting the normal loss rate during standby operations. A larger plug (approximately 18 cm in diameter) is used to retain the SfHe but allow higher vent rates during the transfer operation. The third plug is the thermomechanical pump used to transfer up to 1000 liters/hour of SFHe to the receiver dewar.

A centrifugal mechanical pump is an alternative to the thermomechanical pump, it is being developed by the National Bureau of Standards under contract to NASA-ARC. An attractive feature of the thermomechanical pump is it has no moving parts and requires only a heater. The mechanical pump has a

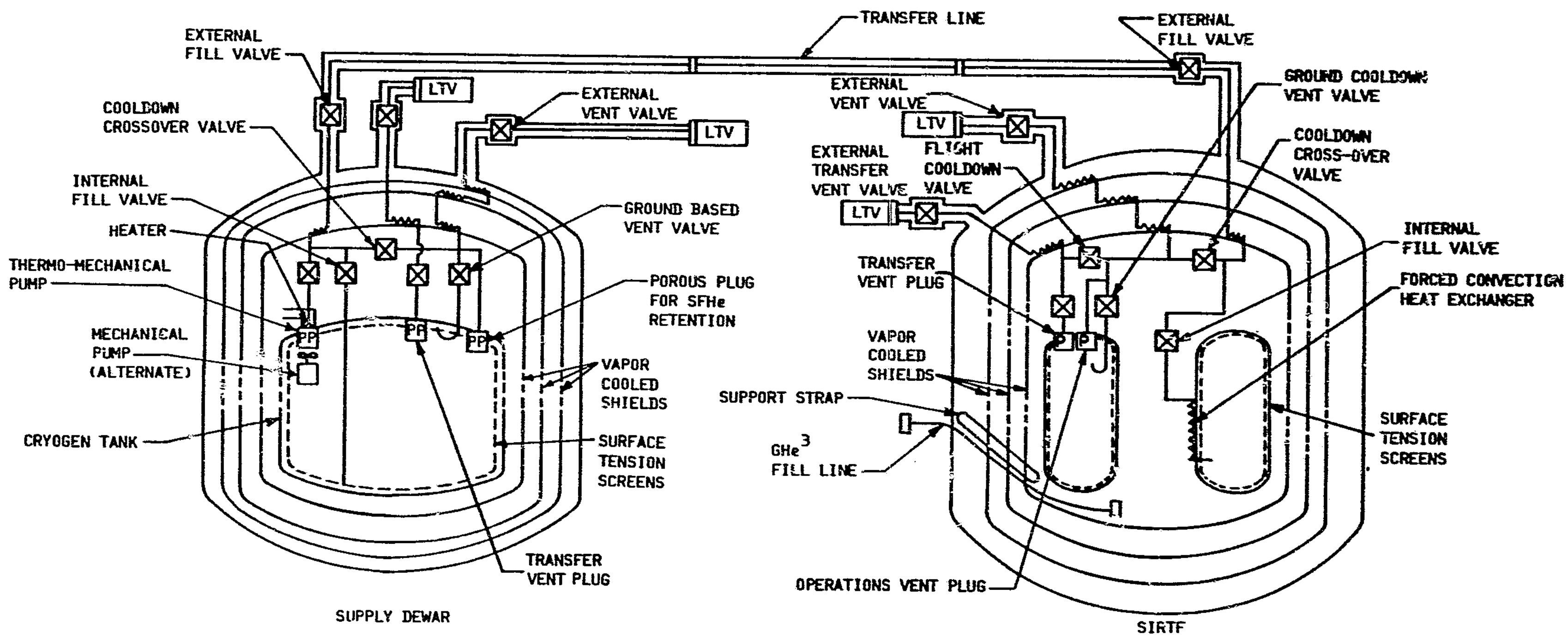

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Figure 2-17 Cryogen Replenishment System

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higher efficiency at fluid temperatures above 1.5K, but the heat from the motor will be partially absorbed in the transferred cryogen and must be vented from the receiver tank. The GHe is vented from the supply tank when transferring with a thermomechanical pump. Both pumps require further development which is presently in progress. Both BASD and NASA-GSFC have thermomechanical pump programs underway, and NASA-ARC is developing a mechanical pump.

The number of valves may vary slightly depending on the flexibility required. The portrayed scheme permits a very large number of options for precooling, venting and operating the supply dewar. Additional components such as temperature sensors, pressure transducers, liquid level and or mass quantity gauging devices will be required. Perhaps a cold flow meter in conjunction with a warm flow meter may be used if adequate mass quantity gauging is not available when required. All lines that may trap cold GHe will be supplied with burst disks and relief valves to avoid excessive pressure which might damage the cryogen tank.

Redundancy is required for Shuttle and Space Station safety. It is not clear when dealing with an inert fluid such as SfHe whether the redundancy required should be redundancy of function or redundancy of components. The existing fluid management scheme provides double and triple redundancy for venting to keep pressure within safe limits. It does not provide redundancy of components. There is only one fill line for instance; the bayonet couplings can have redundant O-ring seals but the fill bayonet as a whole is not redundant. This is an area that needs further definition and study.

2.3.2 Dewar Mechanical Design

The first tradeoff to be made is the configuration of the ASE dewar. A spherical shape will always yield the least weight for the tanks, but there are other considerations besides minimizing weight. A commonly built form of dewars is cylindrical with torospherical heads. A cylindrical tank could

be mounted in the STS bay either axially or radially. After the configurations were sized, a review was made of the existing STS carrier designs, but none were found suitable for mounting the ASE dewar. Therefore it was decided that all configurations should be trunnion mounted on STS sill and keel fittings.

Figure 2-18 illustrates the three configurations sized for 5300 l of LH_2, plus 10 percent ullage. The axially mounted cylindrical configuration is not really a cylindrical inner tank, but two torospherical heads butted edge to edge. The radially mounted cylindrical tank is so inefficient a usage of volume that it was dropped from further consideration. Figure 2-19 shows the two remaining configurations sized for 11,750 l (plus 10 percent ullage) for servicing a warm (300 K) SIRTF.

Table 2-8 lists the relative weights for the two 5300 l configurations. The wall thickness for all tanks were sized by buckling criteria for external pressure. No design effort was made for weight reduction such as waffling or ribbing. Weight reduction for the cylindrical dewar should be more easily attained than for the spherical dewar. The spherical tanks already have minimal walls.

Table 2-9 shows identical trends for the 11,750 l dewars. The cylindrical dewar has much heavier wall thickness in the torospherical heads. Also, it has greater surface area resulting in higher VCS and MLI weights.

<u>Weight versus Length</u>

Another criterion to be considered is the average weight per unit length. The STS can carry a payload of 29,500 kg and the bay is 1830 cm in length. The maximum average utilization is 16.1 Kg/cm. Using the weights from Tables 2-8 and 2-9, and the lengths from Figures 2-18 and 2-19, gives

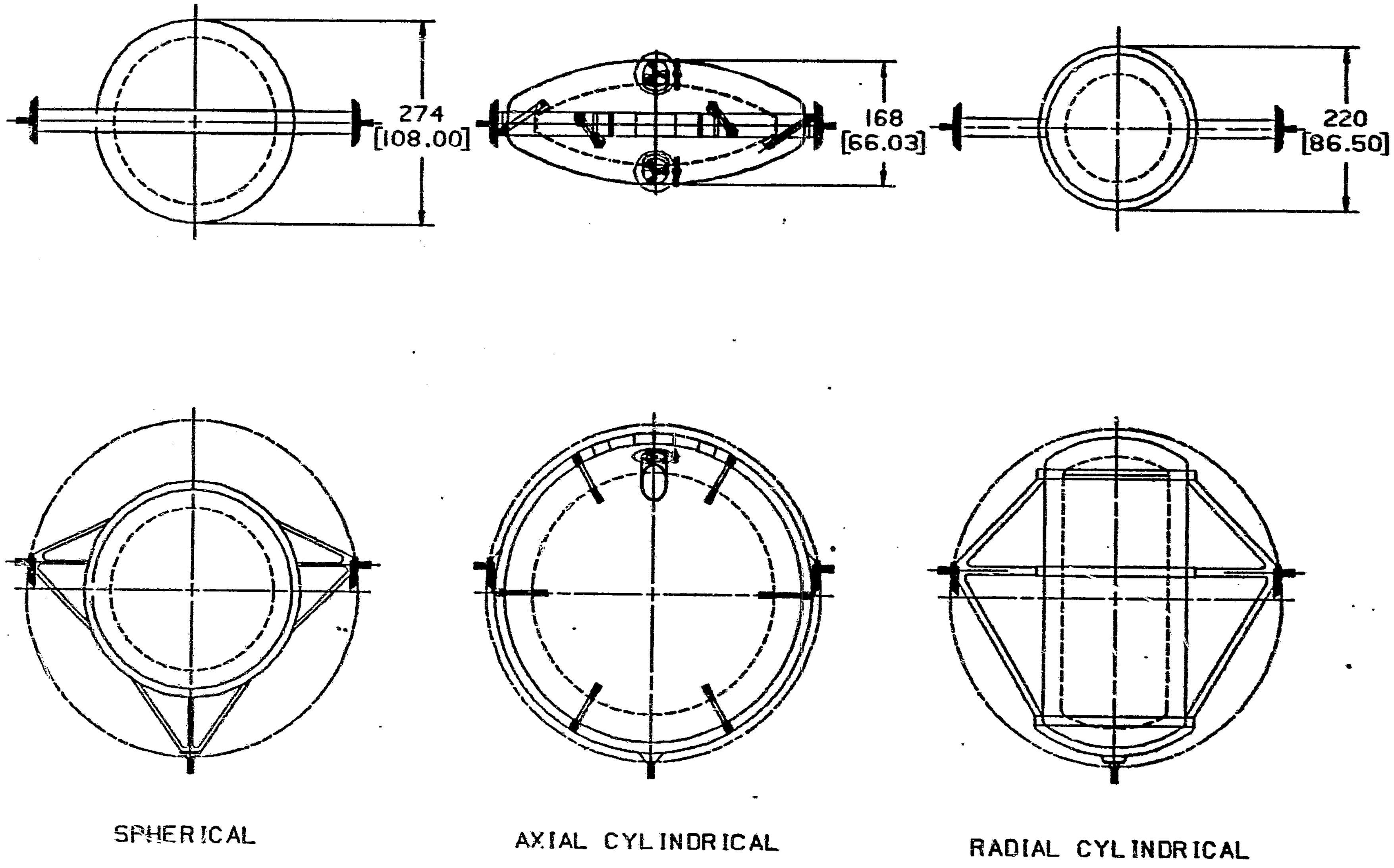

Figure 2-18 5300 Liter Dewar Configuration

Table 2-8

COMPARATIVE WEIGHTS OF 5300 LITER ASE DEWARS

Component	Spherical (kg)	Axial Cylinder (kg)
Inner Tank	210	570
Outer Tank	285	900
Girth Rings	48	49
VCS	160	210
MLI	46	65
Plumbing, Straps	15	16
LHe	665	665
Trunnions	62	30
Electronics	45	45
TOTAL	1536	2550

Table 2-9

COMPARATIVE WEIGHTS OF 11,750 LITER ASE DEWARS

Component	Spherical (kg)	Axial Cylinder (kg)
Inner Tank	331	805
Outer Tank	770	1210
Girth Rings	50	70
VCS	262	310
MLI	69	90
Plumbing, Straps	32	34
LHe	1470	1470
Trunnions	114	63
Electronics	45	45
TOTAL	3143	4097

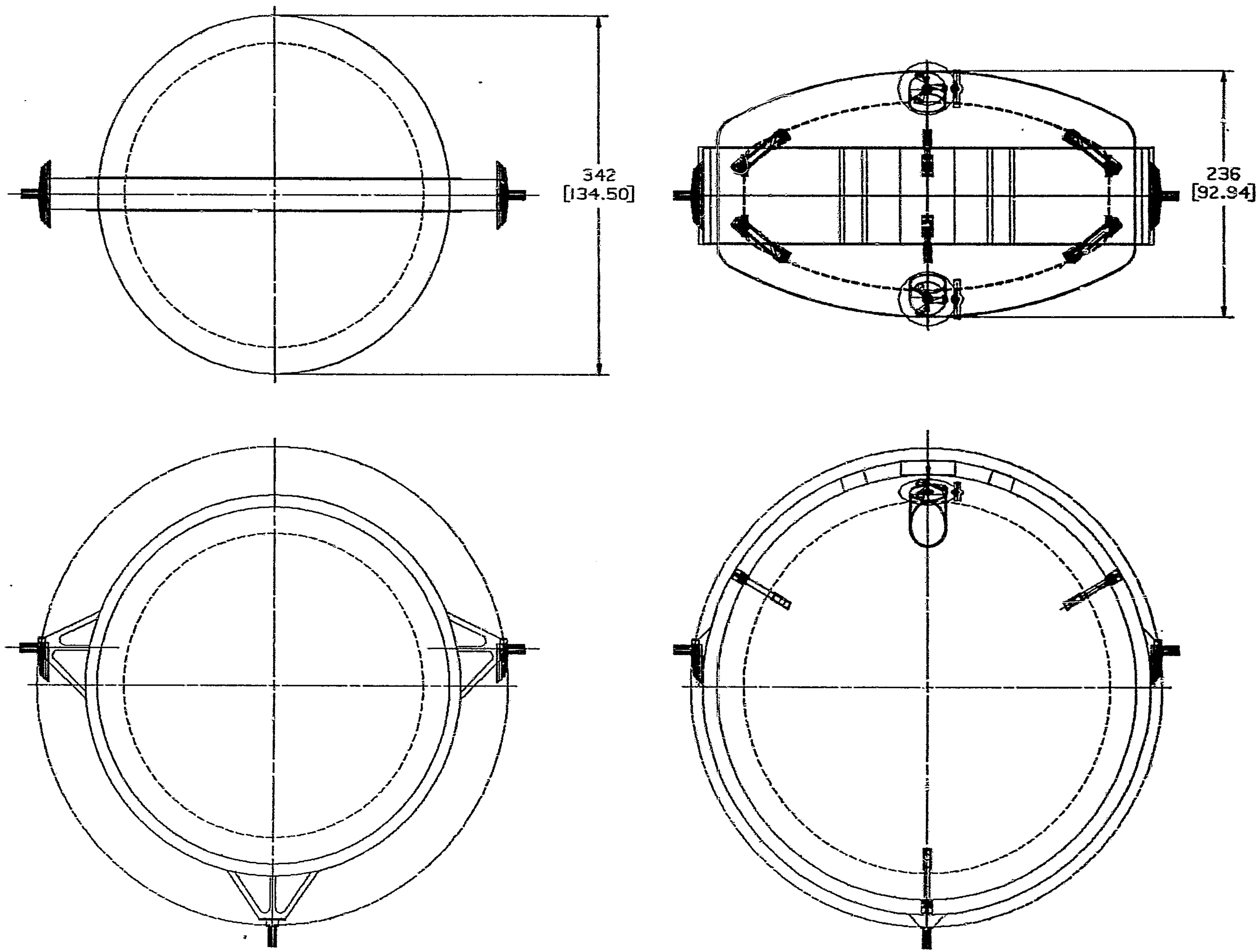

Figure 2-19 11,750 Liter Dewar Configurations

Configuration	Volume (liters) 5300	11,750
Spherical dewars	5.4 kg/cm	9.2 kg/cm
Cylindrical dewars	14.1 kg/cm	17.4 kg/cm

This indicates that the spherical dewars do not utilize their bay length very efficiently and that perhaps the additional weight for cylindrical dewars does not impact launch costs drastically.

Fabrication

Ease of fabrication is a criterion which directly affects cost. Fabrication of the shaped shells for the tanks is about even. They have about the same number of weld seams, but the seams are longer on the cylindrical dewar.

The biggest difference, and the most labor intensive, lies in installing the MLI blankets. Spherical blankets require cutting and hand sewing gore sections. The torospherical shapes are much easier to lay up because they only need to be slit part way. Also the less seams in the blankets, the better they perform.

Versatility

If a spherical dewar is in the design or fabrication stage and the volume of LH_2 requirement increases, all design and hardware must be scrapped and redone. For a cylindrical dewar using the maximum size torospherical heads for the STS, only the cylindrical sections need to be changed in length.

It should prove easier to manifest a shorter length item aboard the STS, given a choice. This is another advantage for the cylindrical dewar.

Conclusions

Unless the extra weight proves a cost driver for STS launch, the advantages of the cylindrical dewar make it the logical choice. Figure 2-20 illustrates the configuration of the 11,750 l ASE dewar. The inner tank and VCS's are supported by six fiberglass support loops from the outer tank girth rings. For space station operations, two grapple fixtures are provided, in order for the STS RMS to hand off the ASE to the space station MRMS. For liquid helium transfer from the STS, no grapple hooks are required. The dewar is fitted with sill and keel trunnions and will interface with the PRLA's at the sill and the AKA at the keel. The ASE is self-contained. The transfer hose is mounted in clips and the electronics boxes and cables are carried between the girth rings. Only the control console is stored elsewhere. Figure 2-21 shows the 5300 l configuration. It is identical except for size.

2.3.3 SIRTF Handling Hardware

On STS

The Multimission Modular Spacecraft Flight Support System (MMS/FSS) is a reusable platform that provides the structural, mechanical, thermal and electrical interfaces between the MMS or other spacecraft and the STS for launch, retrieval, and on orbit servicing. Of interest for SIRTF is a compact, short bay length platform for launch and retrieval of ORU's and docking facilities on orbit.

The FSS consists of three independent cradles identified as cradle A, cradle B and cradle A prime. They are illustrated in Figure 2-22. They can be used in combinations. The A prime is an A cradle with a docking ring which can position and rotate a spacecraft. That capability is not essential to servicing SIRTF. Therefore, a modified A cradle was selected as a candidate, and is shown in Figure 2-23.

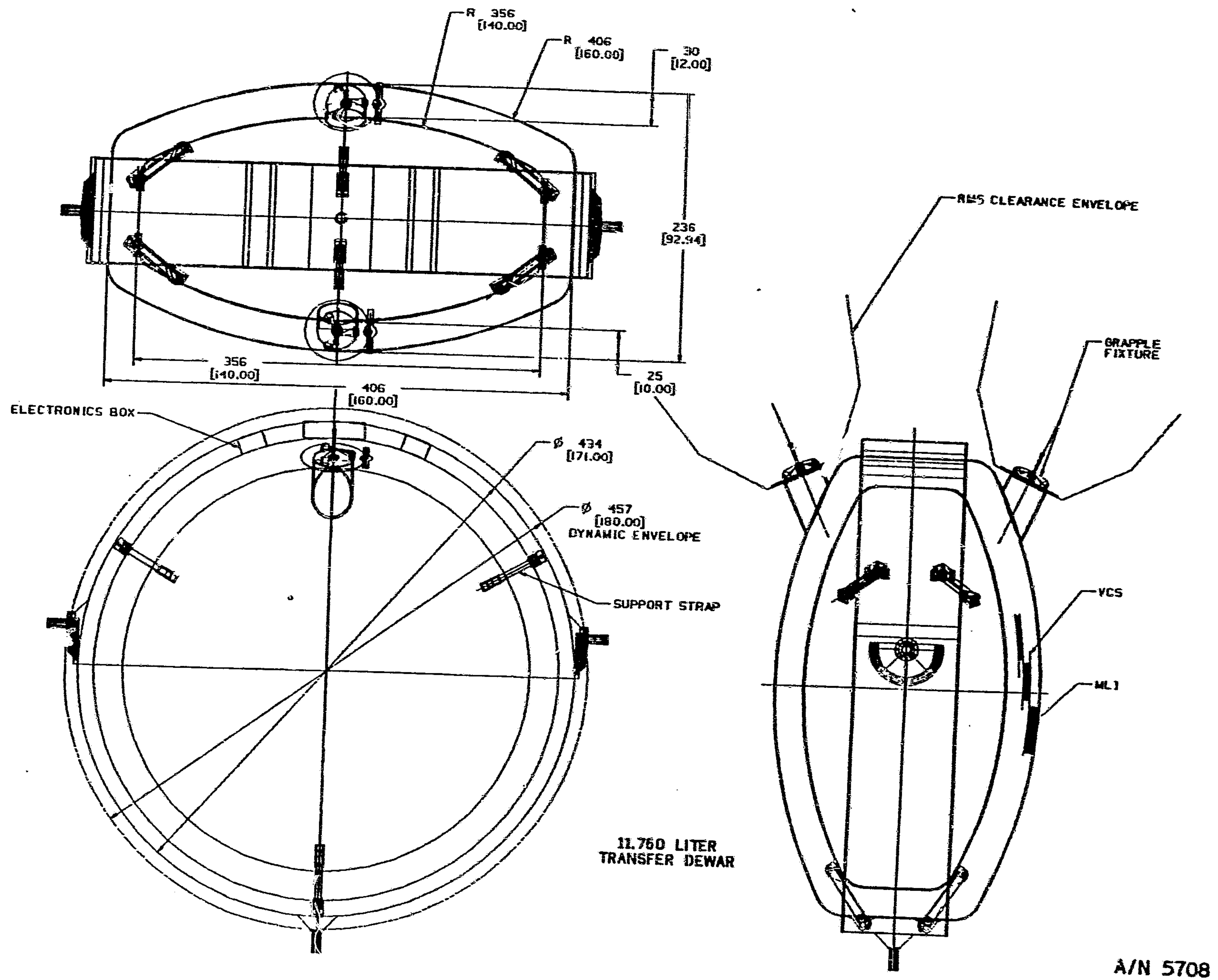

Figure 2-20 11750 Liter ASE Dewar

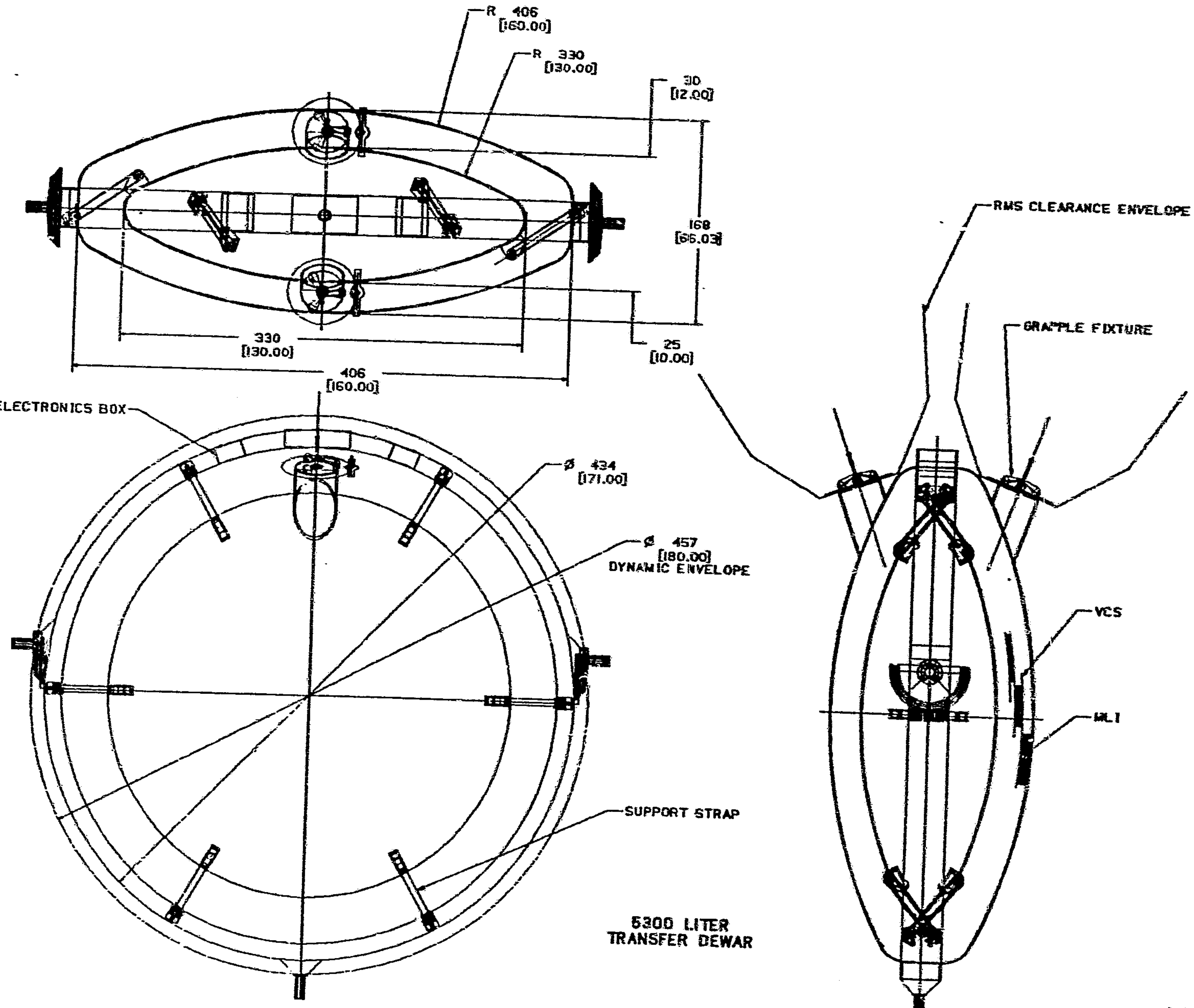

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Figure 2-21 5300 Liter ASE Dewar

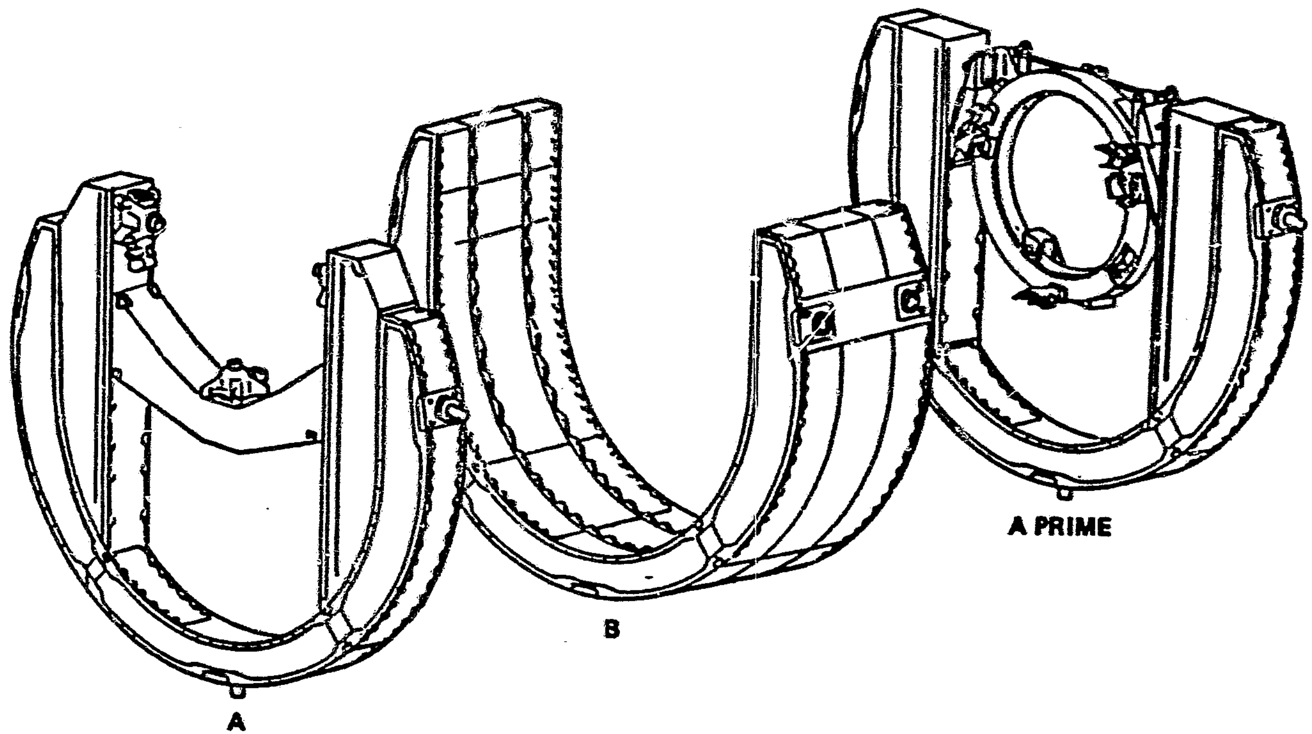

Figure 2-22 Flight Support System

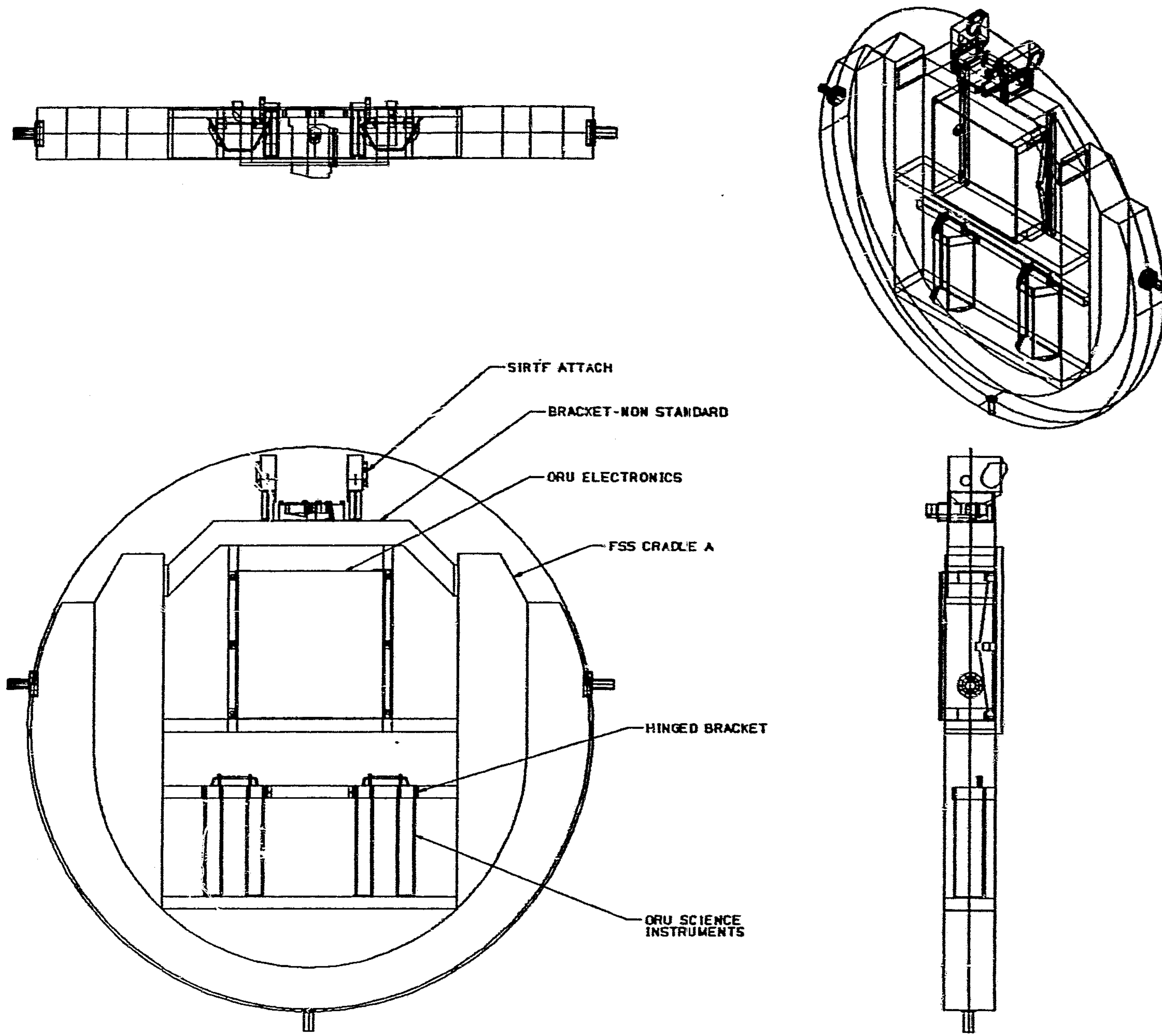

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Figure 2-23 FSS Modified for SIRTF

The modifications consist of replacing the cross brace with an inverted brace with a fixed docking device suitable for SIRTF. In addition, some brackets have been added to provide storage for Orbital Replaceable Units (ORU's). Existing attached points on the A cradle will be used so that the basic unit does not need modification.

Figure 2-24 illustrates SIRTF docked to the A cradle and the STS, at an arbitrary location. The docking interface consists of two pins on the keel trunnion of SIRTF. This type of docking mount has been analyzed for Leasecraft and found adequate during primary and vernier thruster maneuvers.

On Space Station

Both SIRTF and the ASE are trunnion mounted for STS launch, as will other spacecraft which dock with the Space Station. Therefore, it seems logical that the SS will have hardware duplicating the STS sill and keel fittings for a 3-point retention mount, as shown in Figure 2-25. However, when one considers the size of such hardware compared with the 2.7m long sections of the SS, it is not trivial hardware. Since it appears feasible to dock SIRTF to the STS with a close coupled pair of pins on the keel trunnion it should be even more feasible on the SS, since there are less perturbations. The hardware would be much smaller and easier to handle.

2.3.4 Electrical Configuration

For the purposes of this study, a strawman concept of the ASE electronics subsystem was roughed out in order to estimate power requirements of the ASE, establish a framework that could be used for developing self-consistent operational scenarios and to assist in formulating the development planning. It is not intended to be complete or detailed below the subsystem level, but does establish the conceptual footing for the eventual requirements for the overall system.

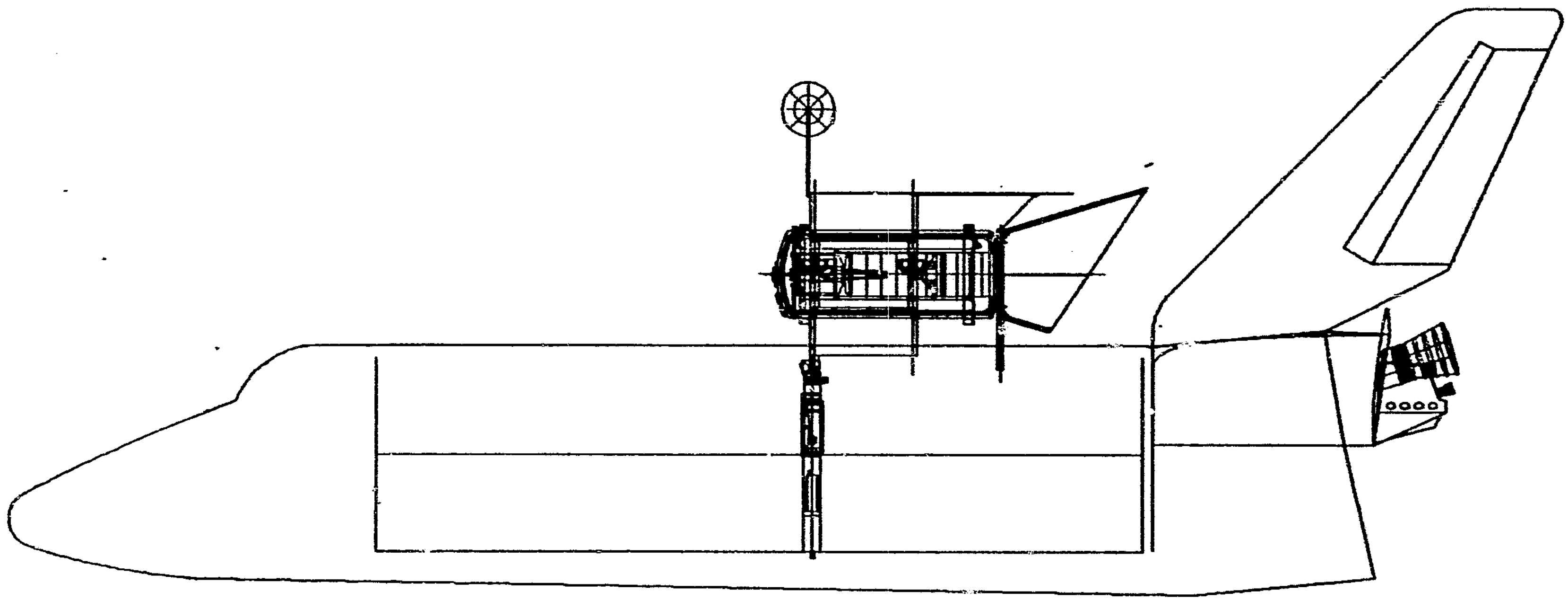

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Figure 2-24 Replenishment on Space Shuttle

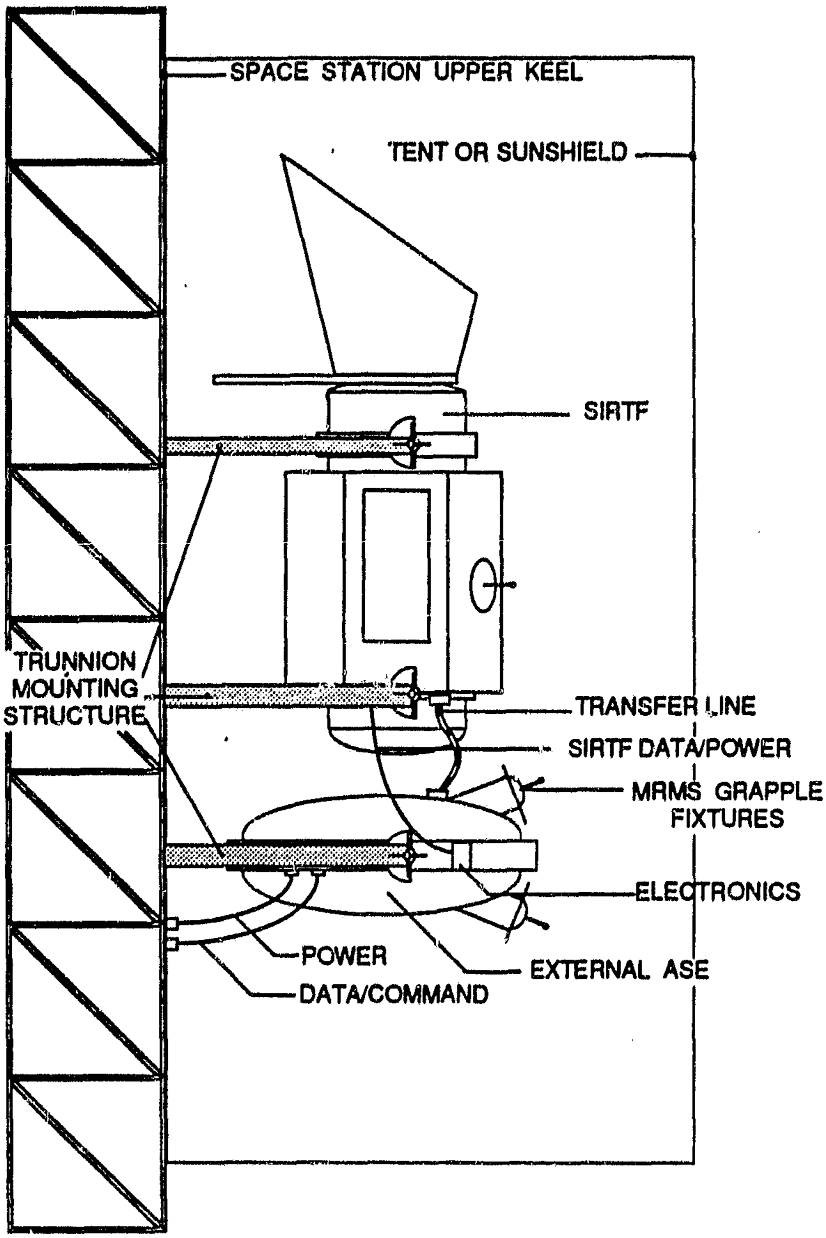

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Figure 2-25 Configuration for Replenishment on Space Station

The electronics subsystem can be divided into two categories: the Dewar or external electronics, which are mounted on the shell of the ASE dewar, and the control or internal electronics which would be located inside a Space Station module or reside in the Aft Deck of the shuttle.

A block diagram of th- electronics subsystem is shown in Figure 2-26. Note that there is a direct connection from the ASE external controller to the SIRTF dewar. It is assumed for reliability and simplicity that a hard line connection between the external and the dewar electronics of SIRTF allowing direct control of SIRTF valves as well as sensor monitoring would be desirable.This gives direct control authority (either manual or automatic) to the ASE system control console for the entire transfer operation. Power to the SIRTF could also be provided through this interconnect if appropriate.

The external electronics consist of:

- Valves and valve controllers- provides drive power, position sensing and current limiting. Eight valves are assumed for the ASE Dewar.

- Temperature Sensor Electronics- Conditioning and monitoring electronics for 40 temperature sensors in the ASE dewar.

- Pressure sensor electronics- High voltage power supply and conditioning electronics for guard vacuum pressure transducers.

- LHe mass quantity sensor and electronics- electronics for the LHe mass quantity gauging in the storage dewar. This is a development item.

- Pump Driver- Power conditioning and logic for the pump system. This is a fully redundant system. This is a development item.

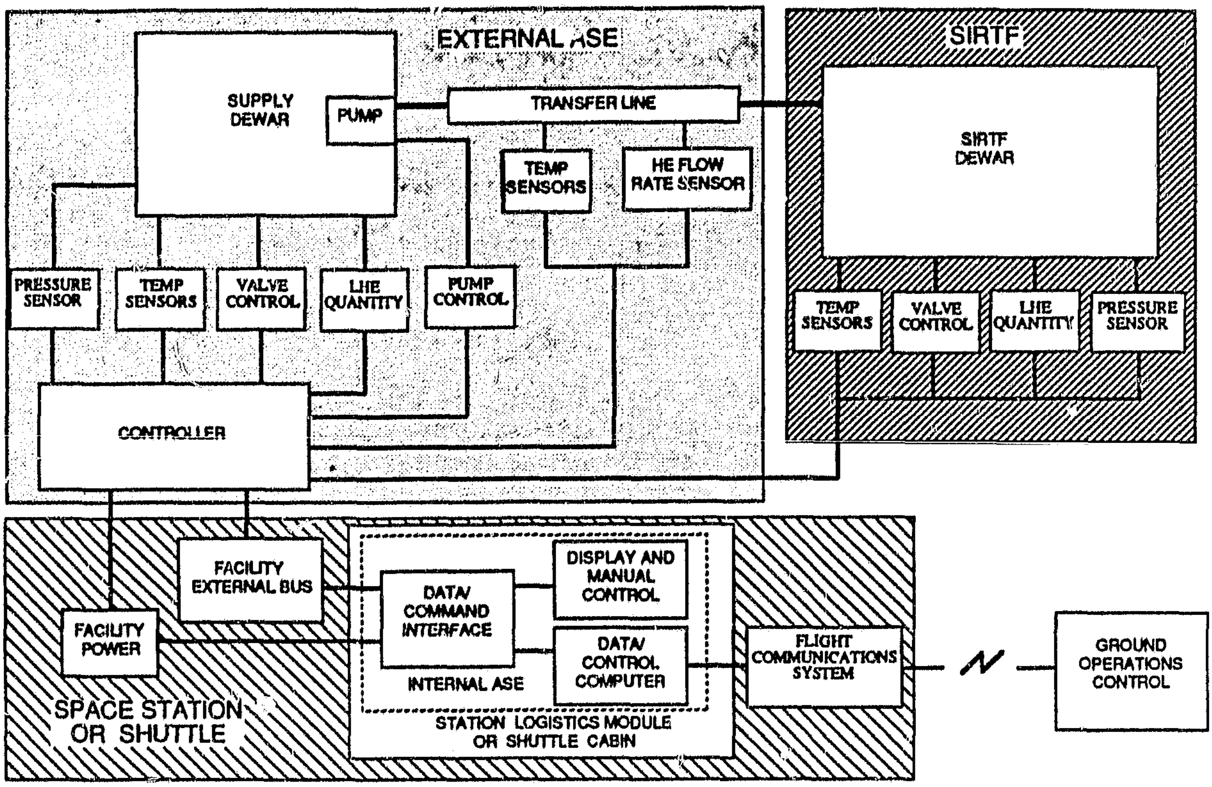

Figure 2-26 ASE Electronics Configuration

- He flow rate sensor- Electronics for in line flow meter or other transducer. This is possibly a development item.

- Barometric valve controller- The vent valve of the ASE dewar opens automatically during shuttle ascent or closes during descent.

- External Controller- Control logic that distributes commands to and collects data from external electronics subsystems and to the SIRTF main dewar electronics. Provides primary power conditioning if required as the interface to either the Space Station or the Shuttle power bus. Interfaces to the Space Station and/or Shuttle data bus to communicate with internal control electronics.

The Command Console or Internal Electronics consists of:

- Data/Command Interface- Device to act as interface from the command console to the Data bus on Station or Shuttle.

- Display and Manual Controller- In the Shuttle this would be the aft deck Standard Switch Panel. On Space Station presumably a similar device would exist. It provides positive manual control authority for valve opening or closure to the crew.

- Data/Command Computer- For acquisition of sensor data and partially or fully automated control sequences used during the transfer operation. The level of automation involved may vary from manual execution of separate preprogrammed sequences to full automated control of the entire transfer, depending on the requirements established at the time. This unit would most likely be a familiar NASA standard such as the GRID computer.

Estimating the number of lines of code for the computer at this time would be premature, but one might get an idea from the fact that the COBE GSE control computer required approximately 1500 lines of code while the computer used for the Orbital Refueling System experiment flow on STS mission 41-G used a software system consisting of 42K words.

- Computer/Telemetry interface- To allow transfer of data to and command from Ground Operations Control.

Table 2-10 shows data rate and power estimates for these electronics. These estimates are extrapolated from the existing COBE dewar.

2.3.5 Performance with Other Cryogens

The baseline (5300 liter) ASE supply dewar has also been evaluated as to performance with other cryogens. The support size was changed to much stronger supports (7.5 x SFHe only) for the heavier LO_2 and LN2. The remainder of the insulation system and tank design is the same. Therefore the dewar is not optimized for any cryogen but is universal for all cryogens stored and supplied at low pressures of less than two atmospheres. The fluid management scheme required for SFHe is significantly more complex than is required for the other cryogens, but all cryogens can be resupplied by the design proposed for SFHe.

The losses of cryogen which might be incurred are presented in Table 2-11. Note that the first column is the ASE supply dewar with the supports proposed for storage of SFHe. The remaining columns show the effect of using supports sized for LO2 and what losses are incurred for a universal supply tank design.

Table 2-10

POWER AND DATA RATES FOR ASE DEWAR ELECTRONICS

BOX	POWER(W)	DATA RATE(BPS)
VALVE CONTROLLER	30	8
SENSORS		
TEMPERATURE	.2	320
PRESSURE	6.0	16
LHe MASS	5.0	16
FLOW RATE	1.0	16
CONTROLLER		
HEATER	5	16
PUMP	50	16
LOGIC BOARD	15	128
POWER		
CONDITIONING	35	
TO SIRTF	55	512
TOTALS	197	<1 K

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Table 2-11

Supply Dewar Performance With Other Cryogens

	Loss in 90 Days (liters)				
		Supports Sized for L02			
Dewar Size	SFHe Sized Supports	SFHe	LH2	L02	LN2
5300	478	1257	608	211	292

2.3.6 Use With Other Cryogenic Payloads

The ASE described here can be used to replenish other helium-cooled payloads smaller than SIRTF. The available volume after a given time on orbit or after filling another payload can be computed using Figure 2-27. This shows the liquid remaining in the 11,750 liter ASE as a function of time (including ground hold time before launch).

Once the SfHe volume required to fill (and possibly cool) a given payload has been calculated, the curve shows directly how long that much fluid will be available in the ASE. Drawing that much liquid out moves the ASE to a new point further to the right on the curve. The amount available for filling another small payload can then be determined.

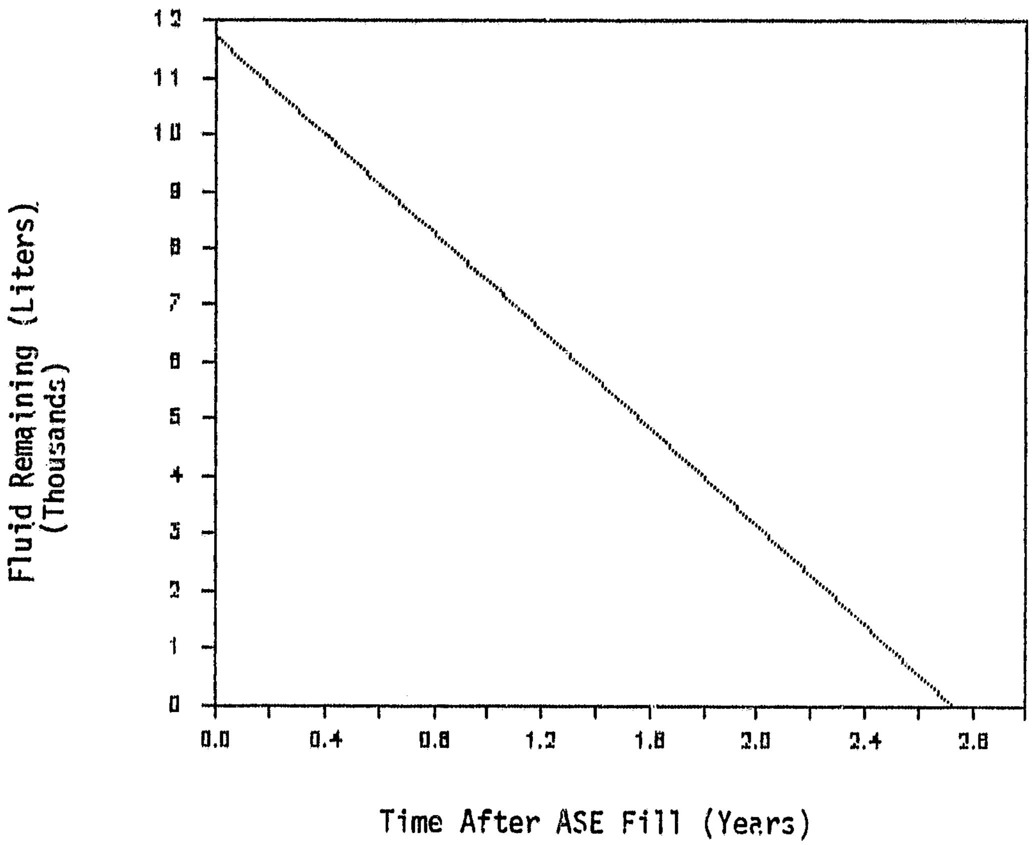

Figure 2-27 Helium Available in ASE for Replenishing Other Cryogenic Payloads

2.4 CRYOGENIC OPERATIONS

The following paragraphs present a list of tasks which must be performed in replenishing SIRTF. A detail discussion of the two major time elements, cooldown, and LHe transfers are then presented.

2.4.1 Operation Sequence

The following table presents the sequence of events for a normal on-orbit replenishment of SfHe. The specific steps are self-explanatory but the method of performing them merits some discussion. This section discusses only the cryogenic operations.

On-Orbit Replenishment Sequence

	Task	Function	Time (hour)
1.	Connect Transfer Line to SIRTF Fill Bayonet	May be connected by Astronaut EVA or remotely. Effect a seal between transfer line, supply dewar, and receiver dewar	1
2.	Connect Control Console electrical cables to supply dewar and receiver dewar	Provides Electrical power and control between supply and receiver dewars EVA or remote	1
3.	Functional check of all components	Verifies system integrity	1
4.	Leak Check	A leak could increase during cooldown and prove a hazard to astronauts suit or other equipment. Pressure decay type leak check.	1

5.	Initiate Cooldown	Open SfHe supply valves and start cooling plumbing and tank (assuming 150K initial temperature).	20
6.	Fill	Will occur automatically after system is cooled. Vent plug bypass valve is closed to retain SfHe in tank. Monitor mass quantity gap. Transfer rate is 1000 liters/hour.	5
7.	Stabilization	Instrument elements may require a stabilization time with associated losses of cryogen.	5
8.	Topoff	Replace cryogen lost during topoff, may be eliminated if instruments are well heat sunk.	2
9.	Position Fluid Management and electrical components for disconnect	Change fill and vent valve position from fill operation to standby	1
10.	Disconnect Electrical and transfer line connections	Disconnect electrical and cables fluid bayonets, remote or EVA	1

2.4.2 Cooldown

As was previously mentioned a series of tradeoffs to determine the sensitivity of the various factors effecting length of cooldown time and quantity of liquid helium required to cool SIRTF were made. A simple SINDA transient model of IRAS was developed with nodes for the metallic conductors, thermal

joints, GHe conduction, and the flowrate of GHe helium. This model was then adapted to the SIRTF configuration and used for the SIRTF cooldown. The IRAS telescope and instrument temperatures lagged the fill line cooldown temperature by some 40 hours. Figure 2-28 presents the model simulation plus the actual fourth cooldown cycle data. The simulation is very good except for the temperature range between 140K and 30K.

To determine the cause of this 40 hour lag cases were run in which the heat conduction coefficient was doubled and a separate case for the metallic thermal joint interface was investigated. The results plotted in Figure 2-29 make it very clear that the metallic joint caused the long cooldown time and the excess cryogen requirements.

For COBE, higher joint pressures on the thermal joints were applied, so for predicting the cooldown rate of COBE, the model used data derived at BASD for joints loaded to 5000 psi and listed in Table 2-12. The GHe heat transfer coefficient assumed was that of pure gas conduction across a boundary layer of 3.8 cm thickness. The predicted cooldown time was 29 hours, and quantity to cool the tank and mass model was 1240 liters. Actual time and quantity to cool COBE was 19 hours and 1190 liters, respectively. Therefore, the model appears to be quite accurate, and if anything somewhat conservative in heat transfers coefficients, probably in the thermal conductance across the metallic joints.

To minimize the cooldown time for SIRTF, the number of straps cooling the MIC and telescope have been increased to six yielding the conductance listed in Table 2-12. The flowrate during cooldown has been made proportional to the cooldown conductance to minimize the quantity of LHe required, that is with high heat loads a larger flowrate is required; with smaller heat loads, smaller flowrate is required to absorb the heat.

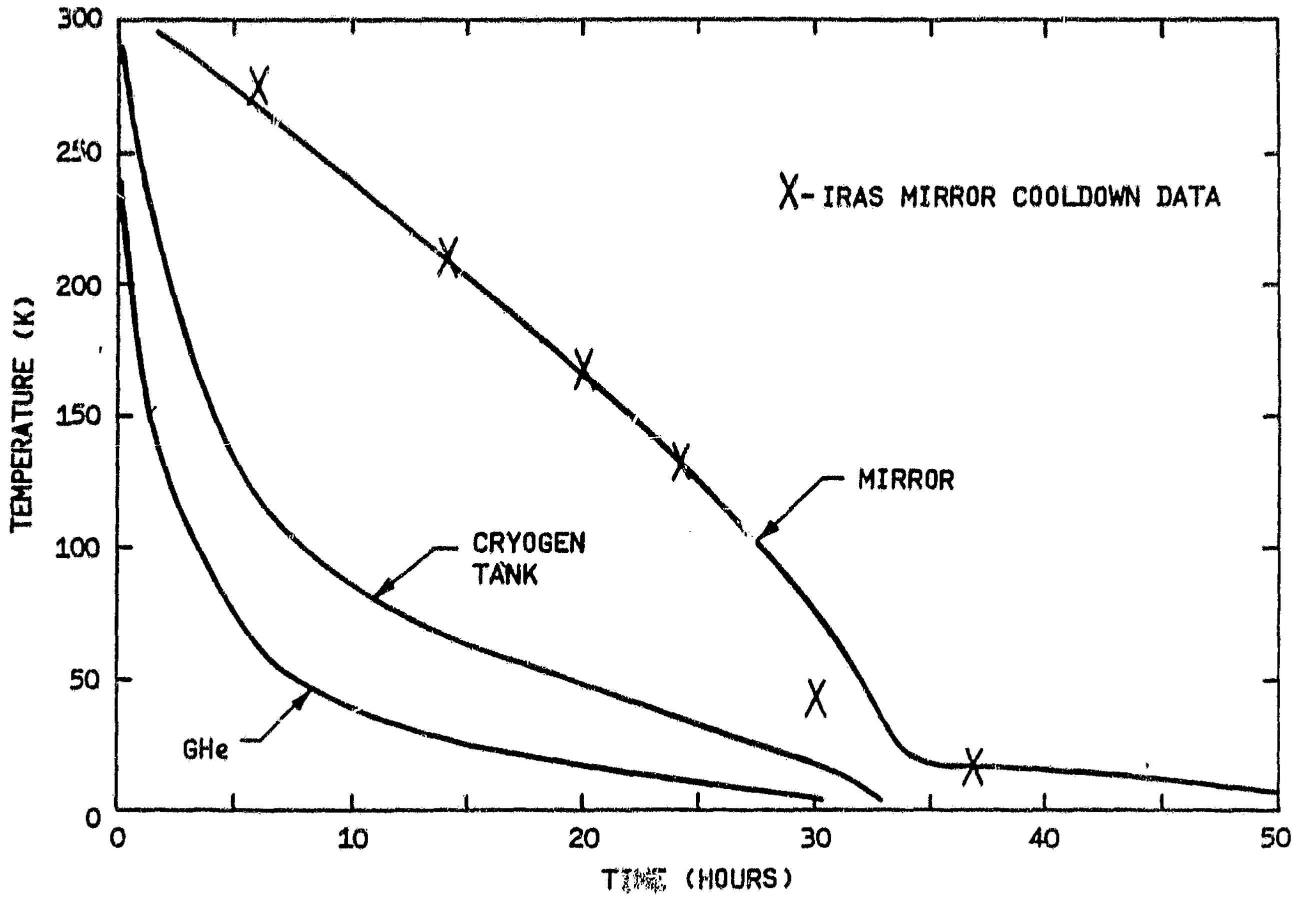

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Figure 2-28 STICCRS Model Simulation IRAS Cooldown Compared to Actual Cooldown Data

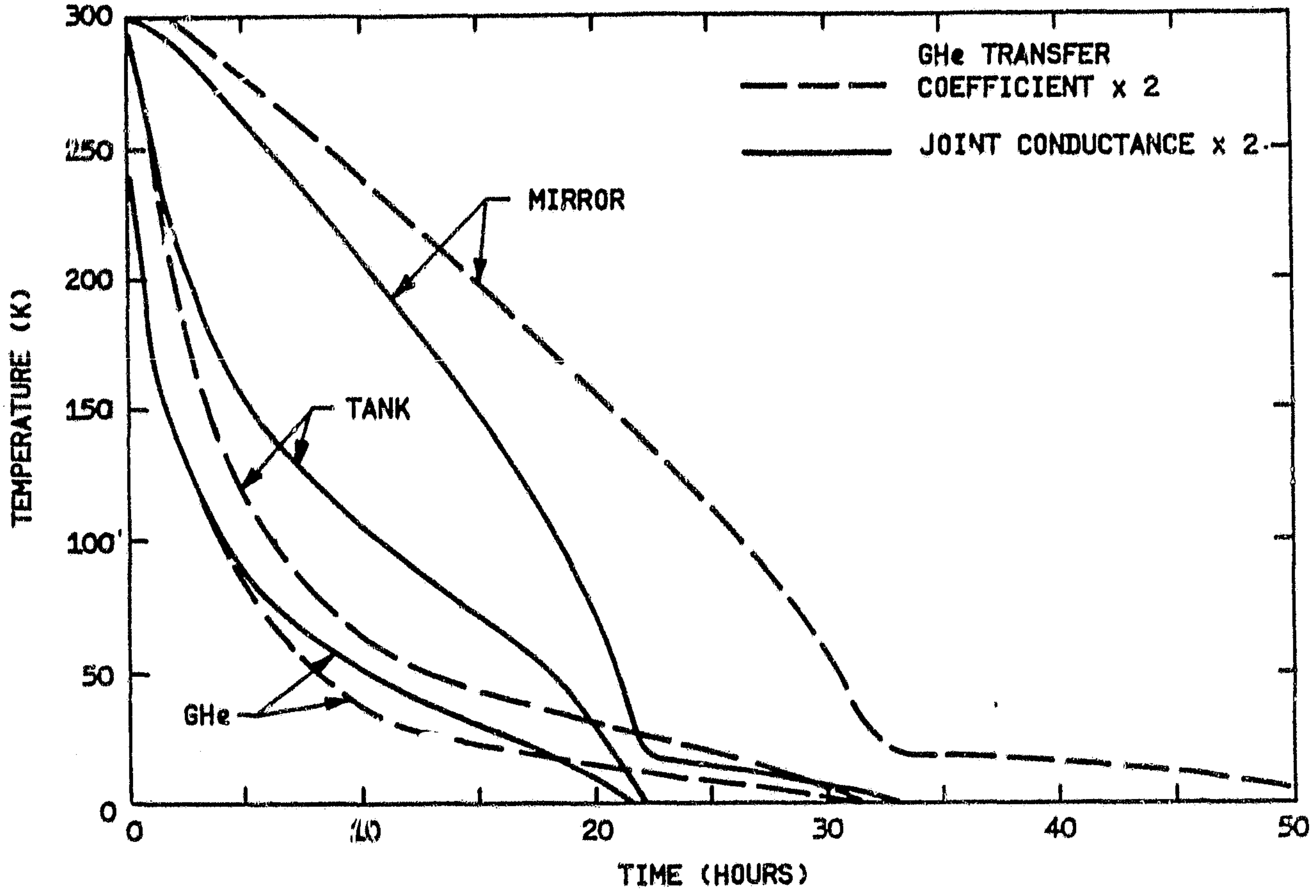

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Figure 2-29 Effect of Doubling GHe Conductance vs. Doubling Thermal Joint Conductance on IRAS Cooldown Time

Table 2-12
Thermal Conductance Across Bolted Joints

Temperature (K)	Coefficient (mW/K)	Number of Joints	Total Heat Transfer Coefffficient (mW/K)
2	200	6	1,200
2-20	1,000	6	6,000
20 & above	4,000	6	24,000

The effects of the metallic joint conductances vs. the GHe cooling for SIRTF is pictured in Figure 2-30. Note that the cooldown for SIRTF can be accomplished in approximately 29 hours if the baselined six straps and high conductance joints are used, whereas doubling the GHe transfer coefficient would require 42 hours to cool down.

Additional analysis was performed in investigating using a forced convection heat exchanger in series with the GHe conductive cooling. The result was to reduce the cooldown time by approximately one hour. At first glance this would not seem to be much benefit but it was incorporated into the cryogenic plumbing design because it gives additional heat transfer at temperatures of 10K and less where transfer coefficients become small. The benefit is that the heat exchanger tube will be the first place to collect liquid helium that contacts the telescope. This will provide either nucleate or film boiling at the telescope/MIC Instrument interface, and provides design margin for fast and efficient cooldown.

An additional concern regarding cooldown is the driving pressure required to flow a sufficient amount of GHe through the plumbing to cool the tank and plumbing. A flow rate of 200 liters/hour was required to absorb the heat cited in Figure 2-31, but for a plumbing system 10 meters long with an internal diameter of 3.6 cm, a driving pressure of one atmosphere is required. If this pressure would be limited to 200 torr which can be easily supplied by the thermomechanical or mechanical pump either the flow will be reduced

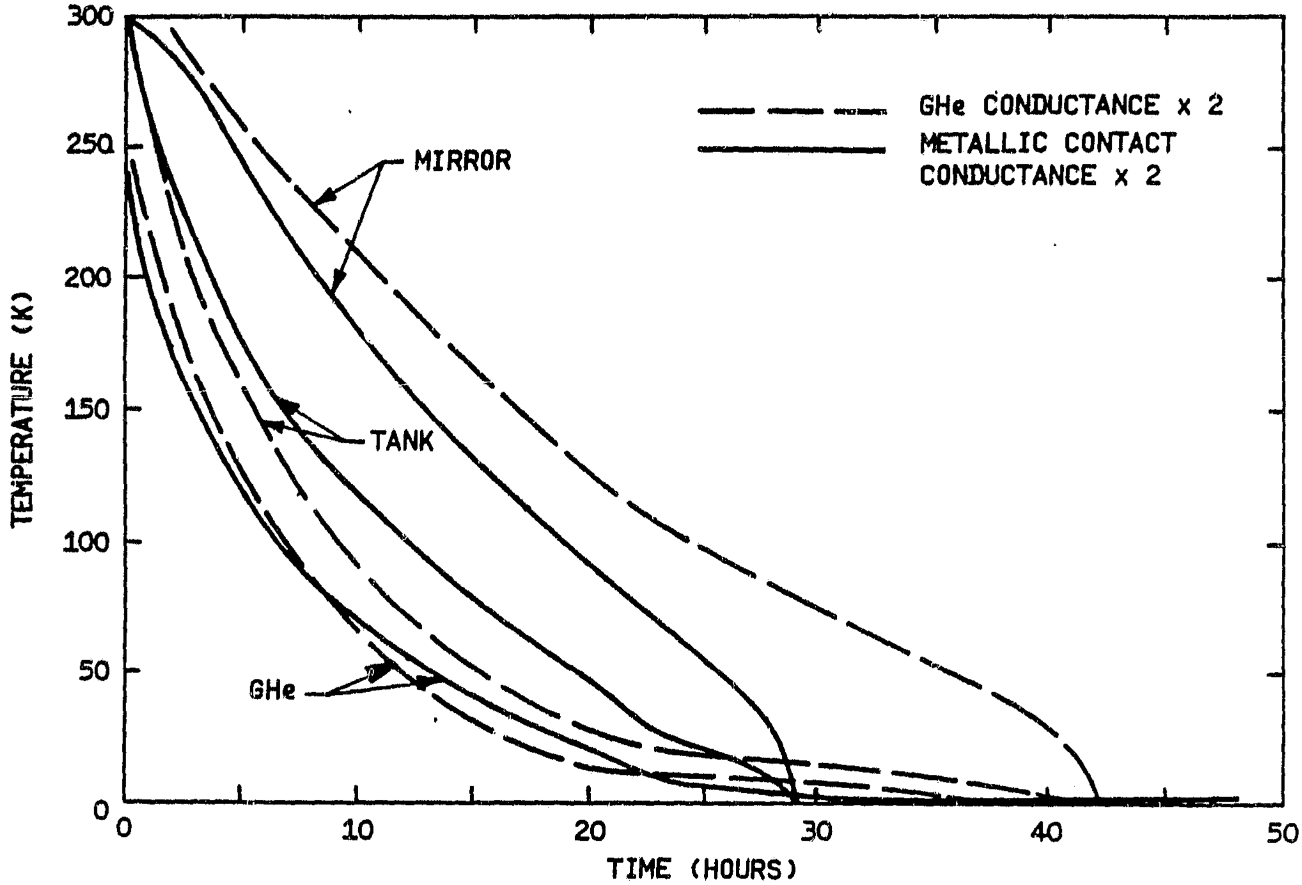

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Figure 2-30 SIRTF Cooldown Sensitivity Analysis

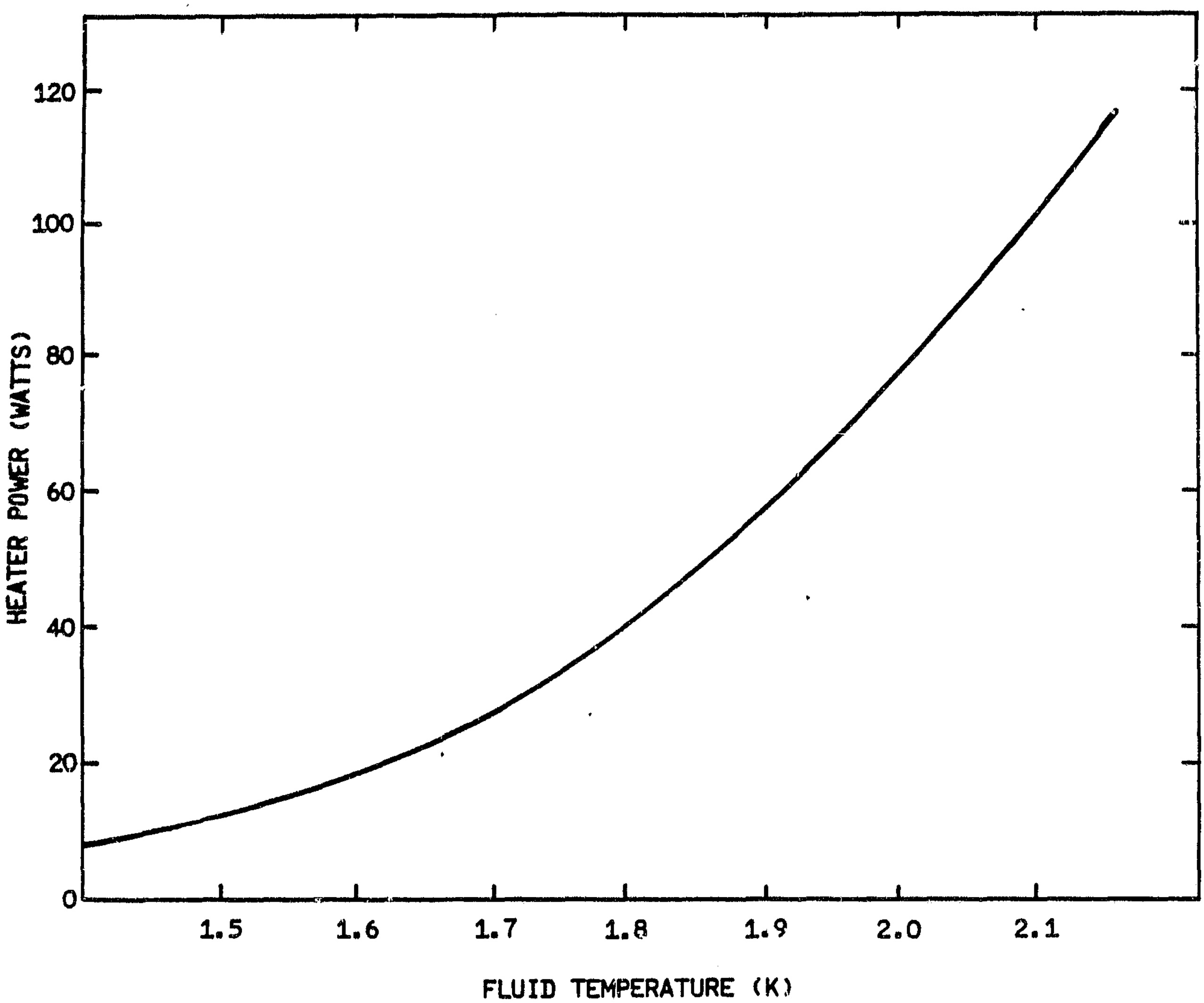

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Figure 2-31 Power Required by Thermomechanical Pump

until the plumbing is cooled to 75K, or the line size must be increased. Fortunately the by-pass transfer line from the transfer vent plug provides a larger (5.8 cm line) which can be accessed by adding a valve. The net result is that the 29 hour cooldown time cannot be achieved with the baseline SIRTF plumbing, but the modified system will permit it.

One area which must be investigated further is the cooldown rate of the glass mirror. If 15K per hour is satisfactory, then we have an acceptable cooldown plan, if not, then the cooldown time must be increased to meet the mirror requirement.

2.4.3 Transfer Rate

For this study an arbitrary value of 1000 liters/hour transfer rate has been taken as a goal and analyzed as to its feasibility. The 1000 liter/hour transfer rate permits filling of the SIRTF system within approximately five hours. Based on the analysis cited in paragraph 2.1.3 and Appendix B we can see that this flowrate results in only a 2.7 torr pressure drop and a 33 millikelvin temperature increase for the steady state transfer using a thermo-mechanical pump. Power required for the various temperatures and flowrates can be calculated using the equation: $Q = \dot{m}ST$

where: Q = power Joules/sec = watts
$\dot{m}$ = mass flowrate grams/sec
S = Entropy - Joules/gm-K
T = Temperature - Kelvin.

For 1000 liters/hour the power requirement is plotted versus temperature in Figure 2-31. One can see that the colder the supply dewar is the less heat required to transfer the fluid. The pressure head developed can be determined by using the London equation:

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$$\Delta P = \int_{T_1}^{T_2} \rho \, S dT$$

where: T_1 = internal temperature - Kelvin

T_2 = external temperature - Kelvin

ρ = density - g/cc

S = Entropy - Joule/g-K

$\Delta\rho$ = Joules/cc = Newton/meter^2 x 10^6

= Pascal x 10^6

For instance with T_1 = 1.6K and

T_2 = 1.7K

$$\Delta P = 0.145 \text{ g/cc } 0.285 \text{ Joule/g-K}$$
$$= 0.004 \text{ Joule/cc} = 4 \times 10^3 \text{ Pascals}$$
$$= 31 \text{ Torr}$$

BASD has taken the laboratory tests one step further and is in process of conducting a large-scale transfer test between 1.6 and 1.8K. Each tank has a porous plug with an interconnecting line which simulates a transfer line. The BASD SFHe flow model has been used to model the test configuration and will be verified by the test.

Additional tests are planned by both NASA/GSFC and NASA/ARC in a series of Hitchhiker tests which will be flown on the shuttle during 1989. The Hitchhiker tests consist of two dewars connected by a transfer line with bayonets. The pump on the initial flight will be a thermomechanical device of approximately 3 micron absolute pore size and capable of transferring Helium-II at rates up to 1000 liters/hour. Unfortunately the dewar sizes are 175/liter and therefore high flowrate tests will be of very short duration.

A second method for transferring the superfluid helium is a mechanical pump as described in References 3 and 4. The mechanical pump concept is a parallel development sponsored by NASA-ARC and being performed at the National Bureau of Standards. At the time of this writing additional flow pressure and efficiency data is not available beyond that published in the two referenced texts, so our comments will be based on that data.

The mechanical pump seems to be a very viable alternative to the thermomechanical pump for transferring SfHe. Performance plots for both normal Helium-I and Helium-II are presented in Figure 2-32. The dates for the two curves are given because the test program in 1975 used different instrumentation and a slightly different configuration for the pump and motor. The helium I performance was improved, therefore, one can expect a slightly improved performance for the pumped SfHe.

Pump efficiency, defined as the ratio of the fluid power to electrical input power, is approximate 30 percent for normal helium. The zero flow pressure head 100 torr for SfHe and 120 torr for normal helium. Flowrates up to 900 liters/hour were demonstrated and 1000 liters/hour should be easily achieved. The power requirement varied from 5 watts for pump speeds as low as 3000 rpm to over 12 watts for speeds in excess of 7000 rpm. The flowrate also varied with power and speed.

The major tradeoff to be made between the thermomechanical and mechanical pump is one of reliability. The centrifugal pump uses bearings and so is subject to contamination and failure, whereas the thermomechanical pump is a passive device requiring a heater only.

2.5 DUAL CRYOGEN SERVICING

The baseline primary cryogenic system configuration under consideration for SIRTF is an all SfHe system. However, an optional configuration for the 28.5° inclination orbit might be a dual cryogen system using solid hydrogen to cool the aperture forebaffle. This section will identify and discuss

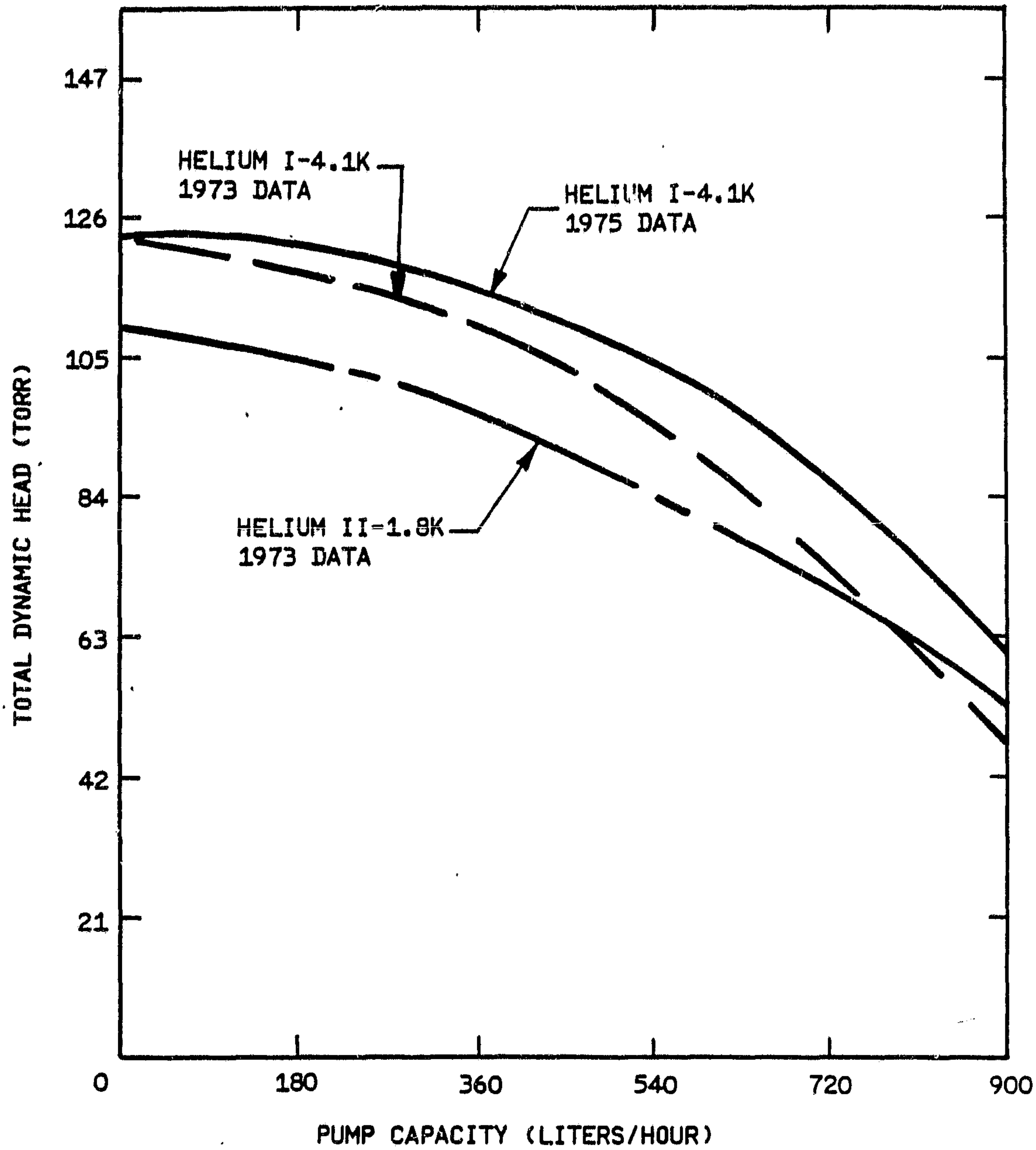

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Figure 2-32 Comparison of Mechanical Pump Performance with Normal and Helium-II

some of the major dual cryogen system servicing considerations plus identify various options which might be used. Also an estimate of the quantity of hydrogen and helium required will be presented along with a schematic of additional airborne support equipment required to service the hydrogen system.

The hydrogen would be used in its solid form; and since it cannot be transferred in that form, some method of transferring liquid hydrogen must be devised. Liquid hydrogen transfer techniques are currently being studied (Reference AG) for LeRC in the Cryogenic Fluid Management Facility (CFMF) experiment (NASA/LeRC Contract 3-23355). The CFMF is a Shuttle payload experiment which will be used to demonstrate the "thermodynamic filling technique" for liquid hydrogen. The CFMF design calls for a supply dewar which uses surface tension devices to acquire the liquid in a low gravity environment. The key characteristic of the thermodynamic filling technique is that the CFMF receiver is filled without venting.

The CFMF chilldown and fill technique is based on the use of lightweight receiver tanks. Even the scale model tanks which are referred to as heavy in CFMF literature have mass-to-volume ratios of less than one sixth that expected for a foam filled toroidal SIRTF hydrogen tank and associated shroud. The energy of the warm tank material is absorbed by raising the pressure and the temperature of the liquid hydrogen in the CFMF receiver tank. For the SIRTF application, this energy must be removed to lower the temperature of the hydrogen to 10K. Because of the much larger mass-to-volume ratio and the energy introduced into the hydrogen, it is expected that a no-vent fill is not practical without complete precooling of the tank.

To pre-cool the SIRTF hydrogen tank a source of refrigeration will be required. Mechanical refrigeration is ruled out by the large power input required to accomplish the cooldown and subsequent freezing. Either liquid hydrogen or liquid helium must be selected as expendable cryogens. If hydrogen is selected, a forced convection heat exchanger will be used in

conjunction with a foam metal "sponge" heat exchanger in the SIRTF hydrogen tank. Further analysis will be required to determine the relative effectiveness of each.

2.5.1 Transportation of Hydrogen

The CFMF experiment will use a 600 liter hydrogen supply dewar (Reference HB). This size of dewar will be inadequate for SIRTF requirements so a second dewar of similar design to the Helium-II supply will be required.

If hydrogen resupply is possible at the Space Station, the SIRTF dedicated hydrogen supply dewar and transportation will not be required. Since hydrogen will be supplied to the Space Station partially by scavenging unused propellant from the Shuttle external tank and transportation on a space and weight available basis, it can be expected that hydrogen resupply of SIRTF at the Space Station will be most cost effective.

2.5.2 Transfer Technique

The precooling of the hydrogen tank will be accomplished by routing cold hydrogen through a forced convection heat exchanger, and then venting it into the hydrogen tank to cool the foam inside the tank. One possible transfer scheme and hardware are presented in Figure 2-33. Once the tank is cooled, liquid hydrogen will start to collect and filling of the hydrogen tank with a closed vent will be completed. The hydrogen then may be frozen by either reducing the pressure over the liquid and retaining it by surface tension in the foam or by passing LHe through a heat exchanger attached to the tank and cooling the hydrogen through conduction in the foam. Other methods have been eliminated because of the large quantity of helium required, or because of risk in venting hydrogen fluid due to low surface tension.

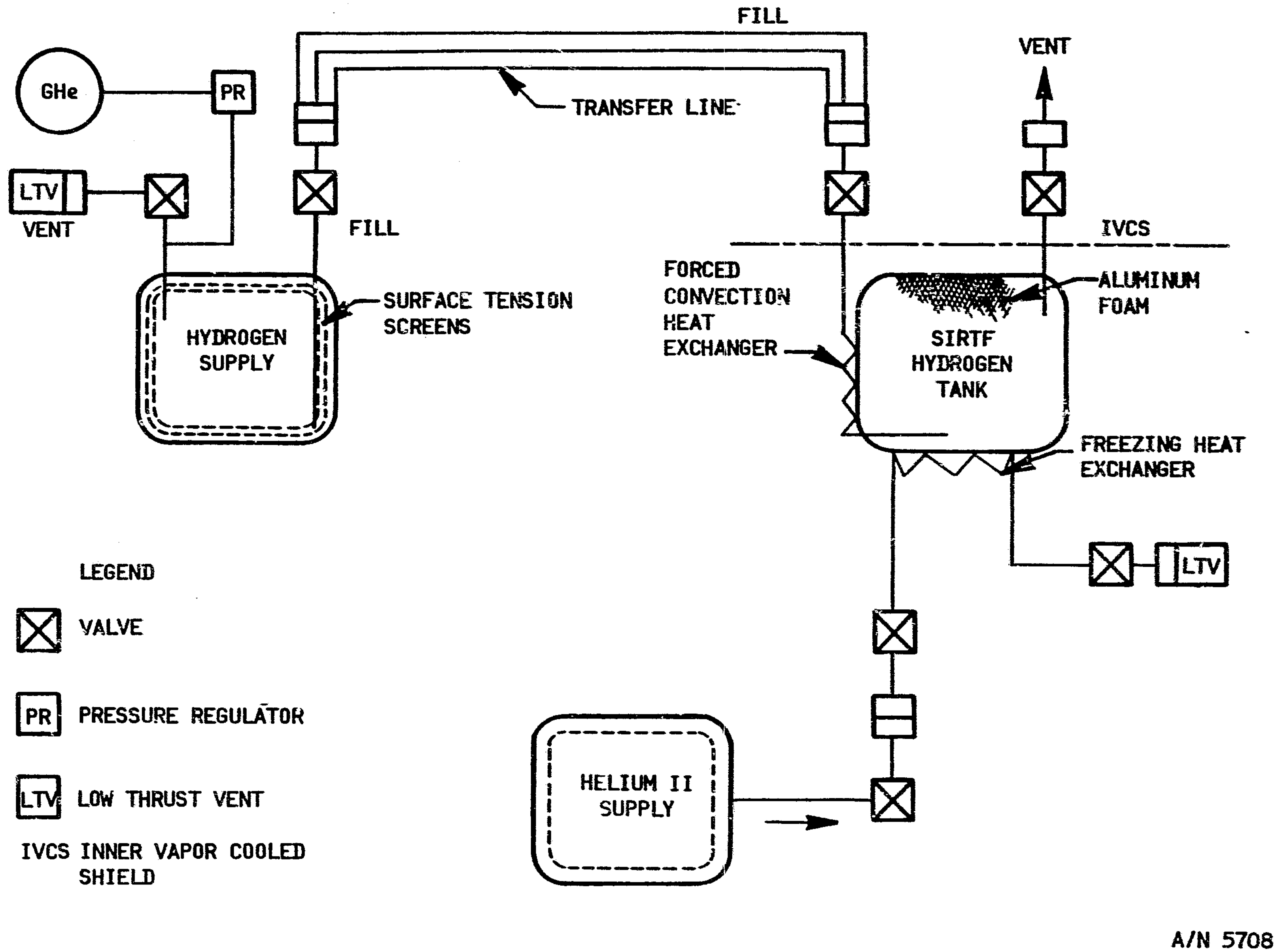

Figure 2-33 Hydrogen Resupply ASE

2.5.3 Hydrogen Conversion to Solid

Table 2-13 shows the various options versus the required hydrogen supply, helium supply, expected life, and fill and freeze time. Table 2-14 shows the liquid hydrogen and liquid helium required to precool the SIRTF hydrogen tank, fill and freeze the hydrogen, for starting temperatures of 300, 150 and less than 20 K.

To arrive at a worst case requirement of helium and hydrogen refrigerants necessary for the various cases, only the latent heat of vaporization was assumed to be used for cooling. The source of helium for these operations would be the helium ASE dewar, and would force the dewar to be larger. The calculations are based on CFMF data and hydrogen properties. Heat exchanger efficiencies have not been accounted for.

The first option shown in Table 2-13, introduces the use of liquid helium to freeze the hydrogen, with a no-vent fill. Precooling of the tank is with liquid hydrogen. This option is the recommended approach because it requires the least development.

It appears that a liquid hydrogen cool down of the SIRTF hydrogen tank, followed by a thermodynamic fill and converting the liquid to solid by slowly venting the tank to space, would be the simplest method to resupply of the SIRTF hydrogen tank in orbit. After the first charge of hydrogen has frozen, the SIRTF hydrogen tank is topped off by introducing additional hydrogen through the vent line. It is expected that approximately 50 percent of the void created by blow down and freezing can be reclaimed in this manner. This method was not selected because of the question of whether the aluminum foam will retain the liquid during this operation. Another drawback is the need to develop a cryogenic metering valve for maintaining appropriate pressure drops across the foam metal in the SIRTF hydrogen tank.

Table 2-13

HYDROGEN FILL/FREEZE OPTIONS

OPTION	LIQUID DELIVERED TO RECEIVER DEWAR (liters)* LH_2 **	LIQUID DELIVERED TO RECEIVER DEWAR (liters)* LHe ***	FILL/FREEZE TIME (hours)
1. LH_2 Heat Exchanger Cool Down No Vent Fill LHe Heat Exchanger Freeze	3500	5600	50
2. LH_2 Heat Exchanger Cool Down No Vent Fill Blow Down Conversion to Solid Two Top Offs	4200	--	95
3. LH_2 Heat Exchanger Cool Down Vented Fill Blow Down Conversion to Solid Two Top Offs	4400	--	100

* For 1650 liters of solid H_2, 2.5 year life.

** Equivalent volume of liquid at 20K density.

*** Equivalent volume of liquid at 1.8K density.

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Table 2-14

CRYOGEN VOLUME

REQUIRED FOR OPTION 1

SIRTF STARTING TEMPERATURE (K)	CONTRIBUTOR	SUPPLY VOLUME REQUIRED LH_2	(liters) LHe
300	Trans Line Cool Down	25	25
	Tank Cool Down	1800	NA
	Fill	1700	NA
	Freeze	NA	5600
	Boil Off	320	500
	15% Margin	580	920
	Total	4425	7045
150	Transfer Line Cool Down	25	25
	Tank Cool Down	490	NA
	Fill	1700	NA
	Freeze	NA	5600
	Boil Off	200	500
	15% Margin	360	920
	Total	2775	7045
<20	Transfer Line Cool Down	25	25
	Tank Cool Down	NA	NA
	Fill	1700	NA
	Freeze	NA	5600
	Boil Off	160	500
	15% Margin	280	920
	Total	2165	7045

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The third option shown in Table 2-13 is similar to the first option except the fill operation is performed while venting instead of by the no-vent fill method. This approach again has design risks, because of the questions of liquid retention in the foam metal.

Section 3
INSTRUMENT CHANGEOUT

Developing a concept for changing out or servicing focal plane instruments and other cold mechanisms requires addressing these questions:

- What are the most important design constraints?
- How should access to the instruments and mechanisms be provided?
- What impact is there on the performance of SIRTF?
- How are the instruments to be changed out, and what are the design impacts on them?
- How are the other cold mechanisms to be serviced?

We address these questions here, and find that on-orbit instrument changeout can be successfully combined with cryogen replenishment.

3.1 DESIGN CONSTRAINTS

Many important design issues will arise in developing SIRTF and instrument hardware that will permit on-orbit changeout. Two issues stand out, however, as critical to determining the overall outlines of the changeout concept: whether the changeout operation can be performed while SIRTF is still cold, and what are the operational constraints associated with extravehicular activities (EVAs) by astronauts.

3.1.1 Warm Versus Cold Changeout

One of the primary decisions that will have to be faced in order to develop a viable approach to instrument changeout is whether or not it is realistic to consider performing the changeout operation while the dewar is still

cold. The main advantage of performing a cold changeout is that it reduces or eliminates the need for the SIRTF dewar cooldown operation during the cryogen replenishment sequence. During the early part of this study, it was felt that this time savings might be significant, especially when considered in light of the current seven day Shuttle missions. However, although starting with a cold dewar represents a savings of 29 hours in the cooldown process and up to 12 hours in dewar thermal stabilization and topoff time, the mission timeline, presented in Section 4.5 shows that the changeout operation and cryogen replenishment of a 300K SIRTF can be performed in less than seven days. That conclusion is true even if contingency time is added to the instrument changeout operation.

On the other hand, there are a number of arguments against doing a cold changeout. These include:

- Misalignment problems that will exist due to the 270 K temperature difference between the instruments being installed and their interface at the dewar. These could be offset by special kinematic design of the interfaces or substantial precooling of the instruments prior to installation. Electrical connectors and mechanical fasteners would require special designs so that they could be physically mated with one half cold and the other warm and still function properly when both halves are at the same temperature.

- Special tooling, lubricants and fasteners would be required to tolerate the temperature differentials without binding or embrittlement fracturing during torquing.

- EVA operations in the immediate vicinity of and inevitable contact with cryogenic surfaces presents a risk to EMU integrity.

- The risk of contaminating a cold optical surface during Shuttle or station based operations.

The issue of cryo-contamination alone, however, is enough to cause us to abandon the possibility of performing a cold changeout. For that reason this discussion focuses specifically on that problem.

Cryo-contamination during Instrument Changeout-

There are several major sources of condensable contamination during change-out:

- Ambient atmosphere at altitude- at 400 km, the nominal atmospheric density is 5×10^{-15} g/cm^3, with a corresponding deposition rate of 0.1 micron/hour or exposed cryogenic surfaces.

  This disposition rate is not corrected for probability of sticking of the species, nor for any shielding features, but it does represent the local environment that must be contended with.

- The local Shuttle environment consists of the following sources of condensable contamination:

  - Orbiter outgassing after bay doors open
    10^{-10} - 10^{-12} g/cm^{2}sec
  - RCS firings
  - water dumps

- The EMU's (suits) present a major hazard with discharges during EVA of

  - 0.72 kg/hr of Oxygen
  - 0.77 kg/hr of water

Of all the possible sources that it will be necessary to contend with, the EMUs are the most the most significant and the most difficult to control without major redesign. The ambient atmosphere and orbiter-produced

contamination can be reduced by the use of some form of enclosure or tent around the back of the dewar. However, since the EVA crew member must be inside the tent while installing and removing instruments, the EMU discharges will take place inside a closed environment open on one side to one huge cryopump, the 2K surfaces of the SIRTF telescope and instrument assembly. Under those conditions, the suit dumps can result in over 50 microns of cryodeposit on sensitive surfaces in the four hour servicing period. Without a significant redesign of the suit itself, there is no way we know of to prevent this problem except to maintain the SIRTF temperature above the condensation temperature of these contaminants. For that reason we recommend that the instrument changeout be performed on a facility that has been heated to 300K before the dewar is opened.

3.1.2 Operational Constraints

The primary constraints of the instrument changeout operation that affect the design of the SIRTF facility and changeout support equipment are EVA compatibility and the overall mission timeline. The general discussion of EVA requirements and the impacts of mission timelines appears in Sections 4.2 and 4.4, respectively. However, the requirements most pertinent to the actual mechanical design of the instruments and facility are summarized here:

EVA requirements

- Crew and Equipment safety- A major safety concern is the compatibility of the payload system/structure with the EV crewman's life support equipment and space suit components. Specifically all equipment "...requiring EVA interface must be designed to preclude sharp edges and protrusions or must be covered in such a manner as to protect the crewmember and his critical support equipment." (JSC-10615)

The equipment that might snag, tear, puncture or abrade a suit must meet the "Edge, Corner, and Protrusion Criteria" specified in JSC-10615. This is particularly significant for the instruments and other ORU's involved in the operation, since it will involve additional design and inspection effort.

- Visibility and lighting requirements- Although illumination is provided by in-bay mounted lights and helmet lights on the suits, stray light rejecting black coatings on the outside of the instruments and the inside of the instrument cavity provide little contrast and hamper the EV crewman's vision. High contrast color coded surface coatings may be required. This will most likely conflict with the facility stray light rejection requirements and will require testing early in the course of the program to ensure that the system level trade between facility performance and changeout requirements is properly performed.

- Restraint provisions at worksite- In addition to tethering requirements for tools and equipment, the proper restraint of the EV crewmember at the worksite is mandatory. Handholds and foot restraints are required to provide reaction force or torques during most operations. Our approach assumes that the Manipulator Foot Restraint (MFR) will be attached to the RMS and be used to provide crewmember restraint during instrument changeout.

- Required working volume- Guidelines for the volume reach of a crewmember constrained by an EMU are given in JSC-10615. The instrument changeout concept presented in the next section follows those guidelines assuming the crewmember is using the MFS. In addition, these criteria need to be applied to the spacecraft design to allow access to external electronics.

Requirements derived from mission timeline- As will be shown in Section 4.4, the changeout operation will require a 6.4 day mission assuming that the opening of the dewar, instrument changeout and dewar closure can be performed in a two man, six hour EVA. Performing the instrument changeout in under six hours should be considered a design goal. The use of an additional EVA to accomplish changeout should only be considered as contingency time. This time limit imposes the following constraints:

- The instrument/telescope interfaces must be self-aligning, kinematic mounts. Any fine adjustments must be made internally to the instrument either automatically or via telemetry.

- Thermal interfaces must be mechanically simple, accessible and reliable with minimum inspection.

- Instrument installation and removal must be mechanically simple, requiring a minimum number of fasteners. A single, clean electrical interface should be considered a design goal. The COBE instrument, with nearly 700 electrical connections requires around 100 pounds of insertion force during installation. Even with the aid of the RMS, this could present problems.

- The dewar opening and closure mechanism must be simple and reliable, to be performed by one crewmember with RMS assist.

3.2 DEWAR ACCESS

The first requirement for allowing on-orbit changeout of the focal plane instruments is to provide access to them through the dewar envelope. This requirement also produces the biggest impact on the SIRTF design and performance.

3.2.1 Alternatives

The BASD study proposal contained six concepts for accessing the science instruments in the SIRTF MIC while in orbit. One concept involved removing the entire telescope with the MIC through the front aperture. The other concepts involved access to the rear, either by removing the entire cover or individual instrument covers.

One of the main goals of this study was to make changeout as simple and easy for the EVA crew members, and as safe as possible. Figure 3-1 shows the baseline SIRTF configuration. One can see that it is feasible to remove the telescope and the MIC through the front aperture, but not easily and not without hazard. It is not simple to access blind fasteners and connectors 4 meters inside an annulus but it is feasible. Captive guides could be employed, and rails provided to guide the telescope in and out. Also, an additional mounting scheme is needed to stow the 5.2 meter telescope either on the STS or the SS, while changing out experiments. The only advantage to front aperture changeout is that the vapor cooled shields and multilayer insulation are not disrupted.

When considering rear access, it is necessary to remove the vapor cooled shields and MLI. It is also necessary to reinstall the shields so that they are conductively coupled to the shields not removed. This can be done using flexible copper straps with screw fasteners. The astronaut would have to have access through the MLI and unscrew perhaps a dozen screws per shield, and manually handle and stow four shields and the external cover. This is not simple or easy for a gloved crew member. Therefore, it was decided that the shields, MLI, and cover should be removable as a single assembly.

3.2.2 One Piece End Closure

One way to accomplish one piece end closure is to use the shrinkage of the cylindrical shields for a shrink fit on the head shields as the dewar is filled with liquid helium. The vapor vent lines are attached to the

cylindrical shields so that no plumbing connections need to be made. Therefore, during fill, the cylinder shields will contract first and shrink onto the head shields. By combining the right materials, a pressure between shields will result providing the necessary conductive path. And, when the dewar is warmed sufficiently, the shields will automatically separate.

Figure 3-2 illustrates the one piece end closure. Besides the shrink fit of the shields, there are two other aspects which must be controlled. These are the attachment of the shields to the cover and the control of the MLI blankets at the separation plane.

The head shields are shown attached to the cover and to each other with nested fiberglass tubes. The tubes are aligned toward the center of curvature of the cover and head shields to accommodate the shrinkage of the heads as they reach their different temperatures. The three sets of support tubes slide relative to each other. The angle also accommodates support in a 1 g field in any position, and are sized for this load. The tubes represent thermal paths from one temperature zone to another, but fiberglass is a poor conductor and the tube walls are thin (0.5 mm) so the effect is not significant.

Of more significance thermally is the gap that will occur in the MLI. As the cylinder shields shrink radially, they will also shrink axially while the head shields will remain in place until there is sufficient pressure due to the shrink fit to lock them together. By then, a 3 mm gap will exist in the MLI. The thermal impact of this is discussed in Section 3.3.

Care must be taken to control the MLI at the gap. Although there will be radiation tunneling due to the gap, this can be minimized by having each layer viewing its opposite layer at the same temperature. Figure 3-3 illustrates a method for controlling edge locations of the thicker layers of MLI. An outer layer of Kapton (0.25 mm thick) is held by hollow fiberglass pins to the shield. This will help prevent sag and control the location of

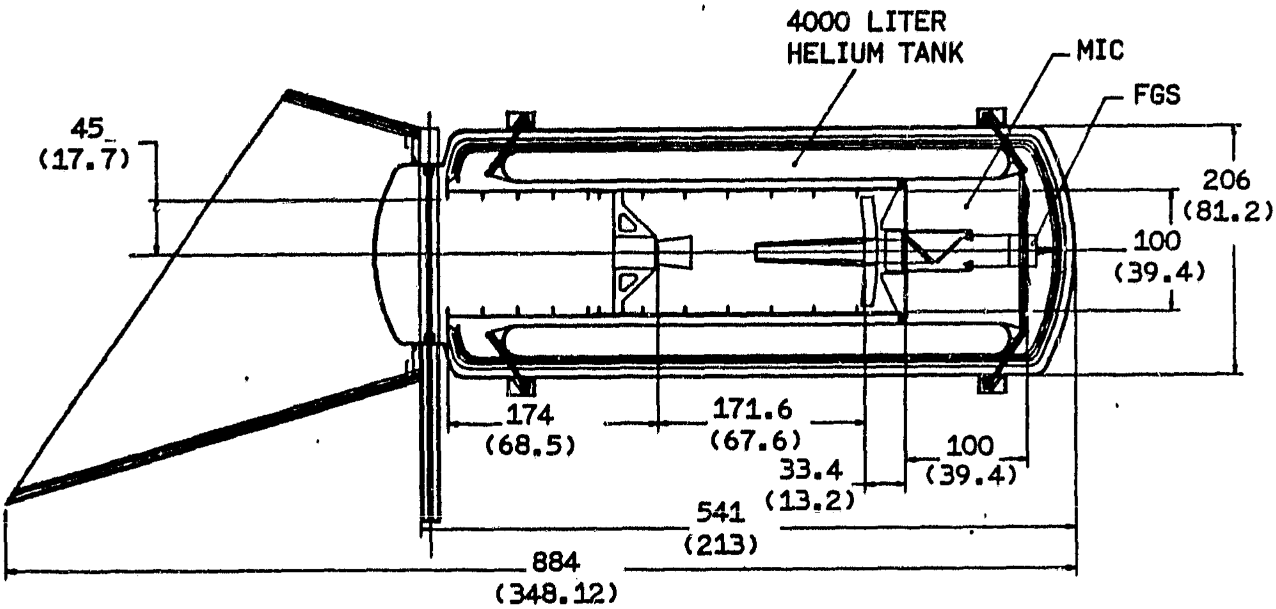

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Figure 3-1 Baseline SIRTF Concept

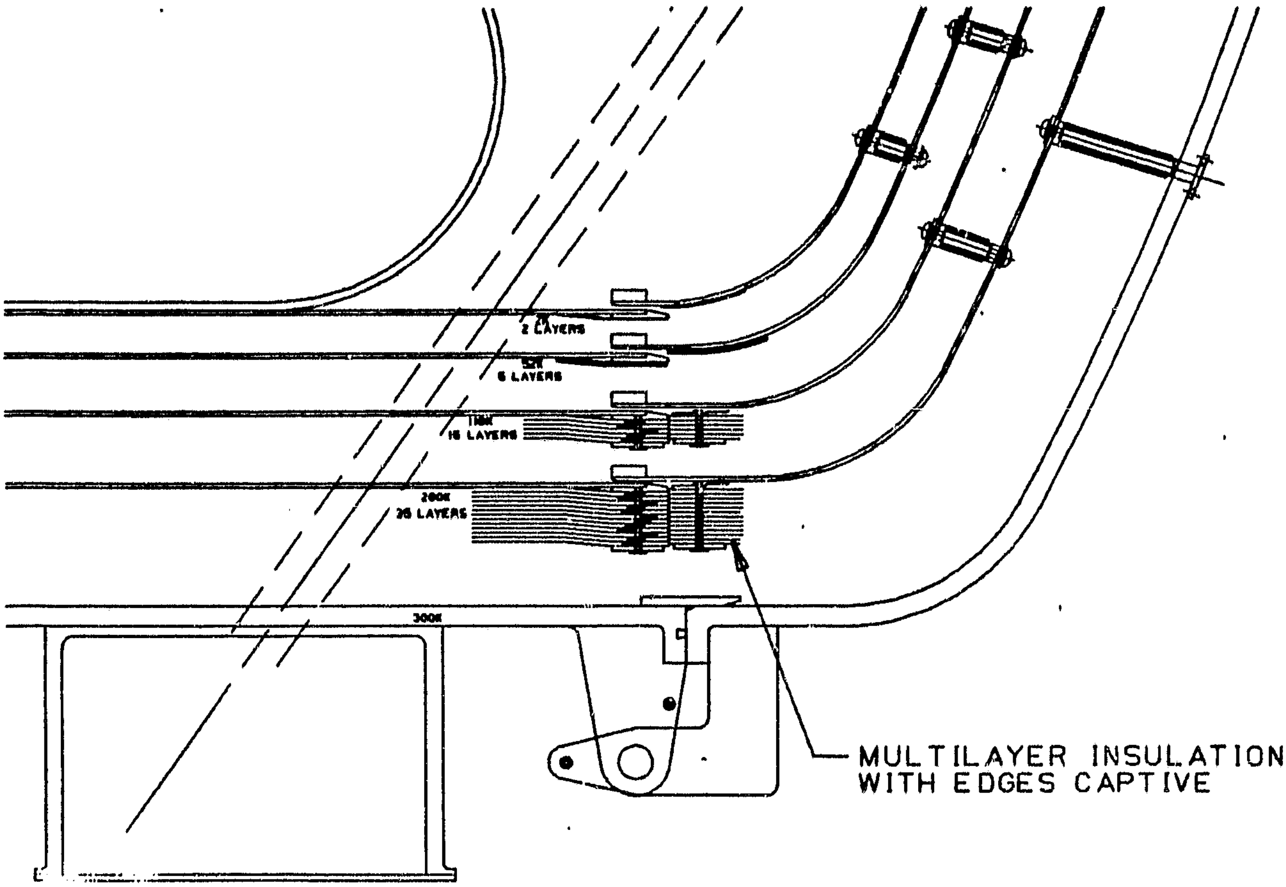

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Figure 3-2 Shrink Fit Thermal Connections For Easy Rear Access

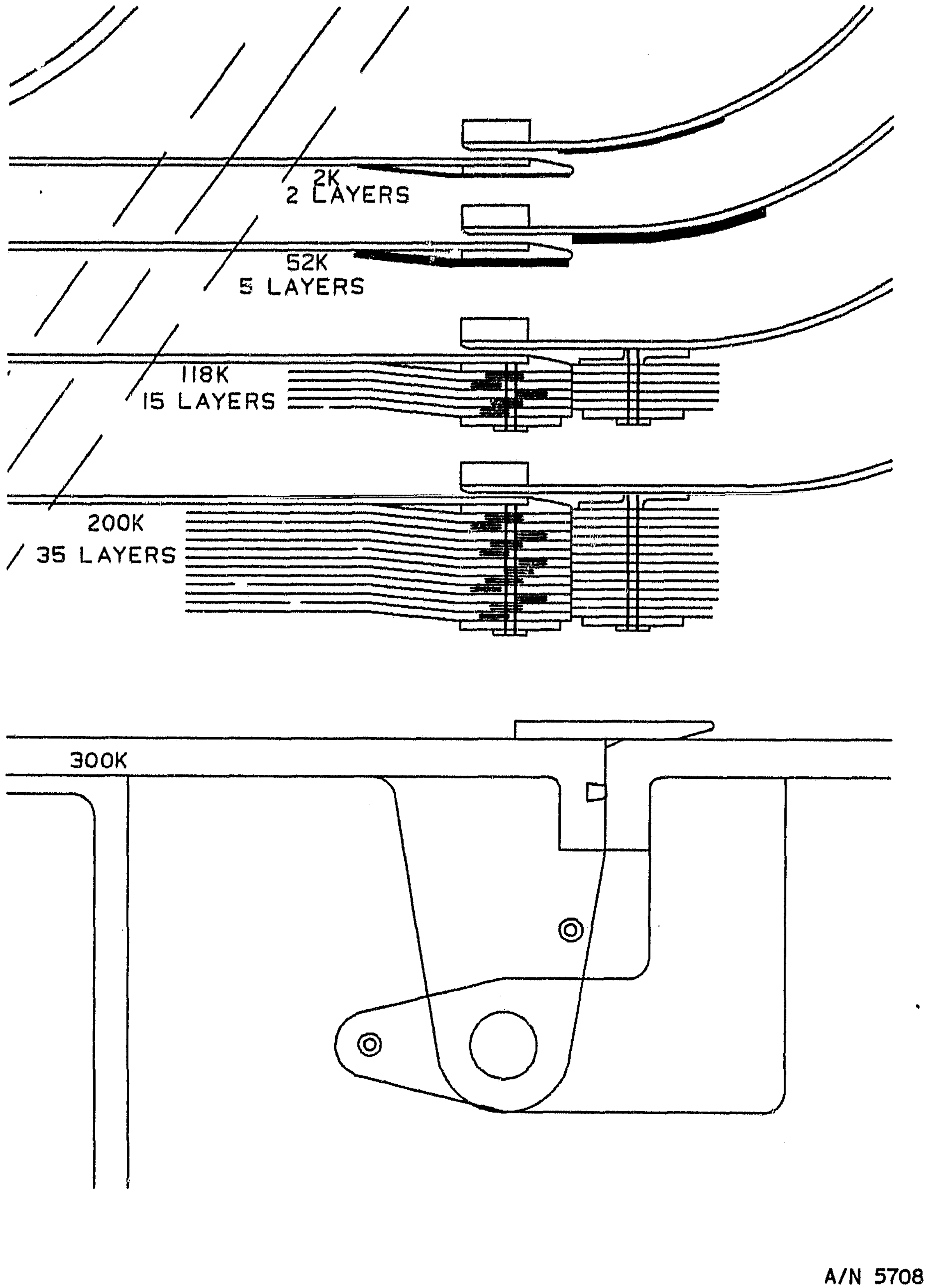

Figure 3-3 MLI Control At Separation Plane

the feather-like blanket edges. How many pins are required and a method of installation has not been evaluated.

Finally, it was decided that the one piece end closure should not be removed at all. A pair of hinges provides the stowage of the closure during access as well as a means of guiding the shield heads and cover into alignment. Figure 3-4 shows the cover assembly rotated open at 5°. The crew members activity for accessing the MIC has been reduced to an absolute minimum - opening a hinged door.

If access has been made simple on orbit, it will provide direct benefits on the ground during hardware assembly and test.

3.2.3 Shrink Fit Analysis

Although initial hand calculations showed that shrink fitting the shields together would be possible, it was decided to do a more accurate analysis to determine the sensitivity of the fits to manufacturing tolerance. The analytical results are given in Appendix E for all four shields. The data was put in graphical form for the inner shield (largest ΔT) and outer shield (smallest ΔT) and these are shown here.

Figure 3-5 gives the pressure between shields as a function of the initial radial gap, for two different thicknesses of an Invar ring inside the outer aluminum head shield. Since the ΔT is only 100K, a large difference in coefficients of expansion is required to maximize the initial gap; hence, the use of Invar.

The slope of the lines shows that the pressure is quite sensitive to the initial gap. To get from 5 to 20 psi pressure the gap must be held to 0.010 to 0.040 inches, for the 0.100 inch thick Invar. It is equally sensitive for the 0.25 inch thick ring, but covers a greater range. Figure 3-6 shows the stresses resulting from the pressure, and the stresses are rather insensitive to change in gap. It can be seen that the stresses are smaller

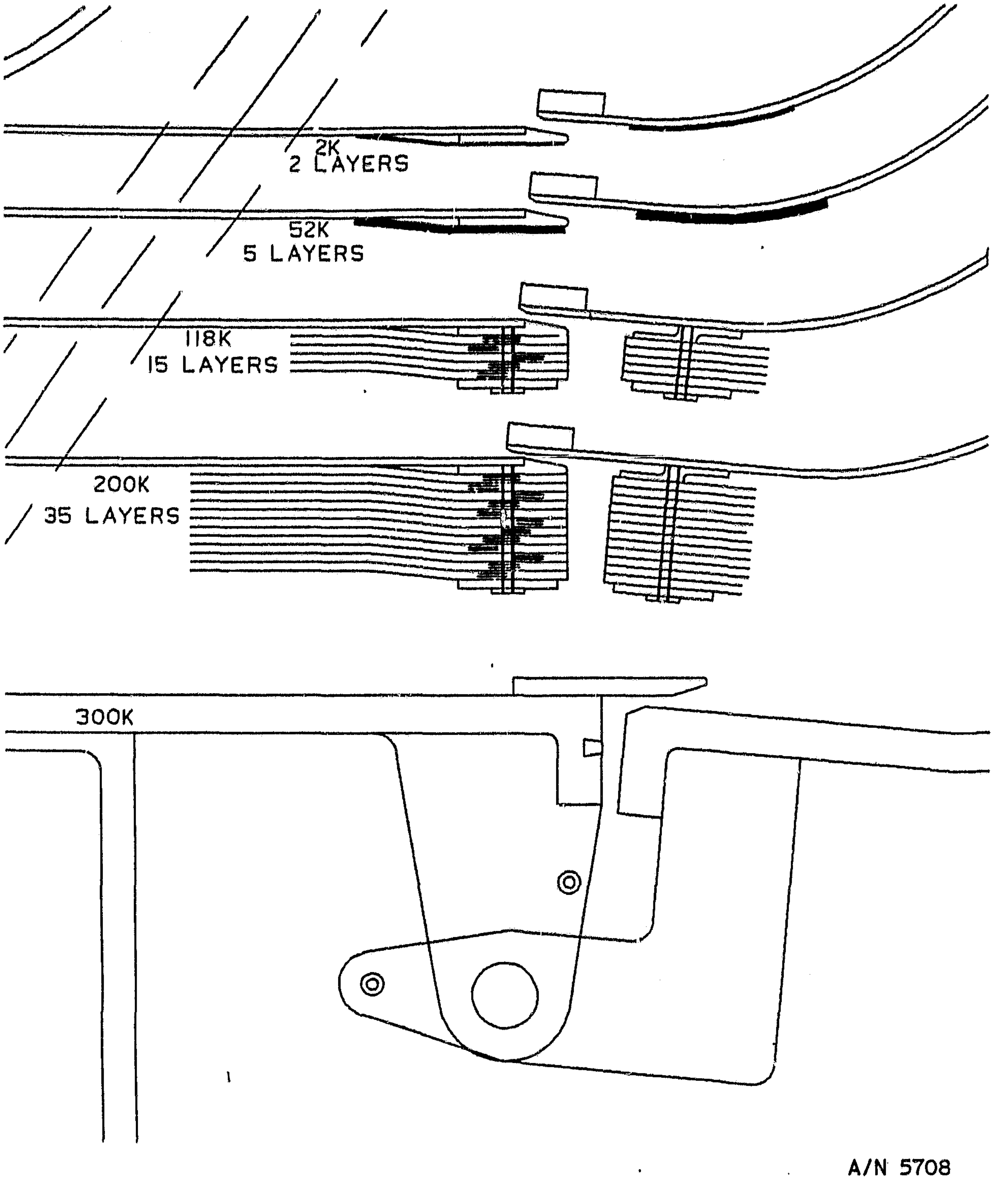

Figure 3-4 Rear Cover Assembly 5 Degrees Open

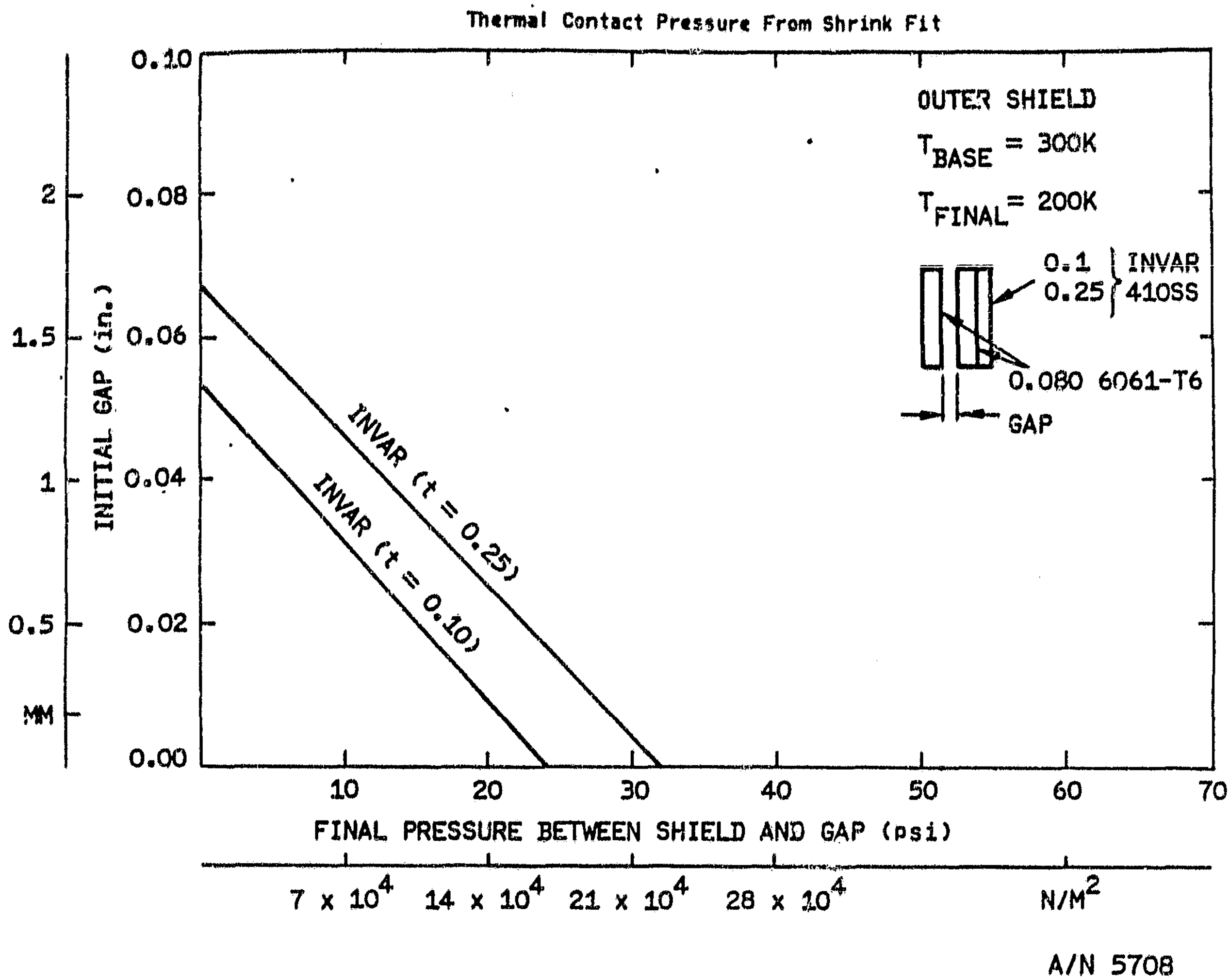

Figure 3-5 Contact Pressure On Outer Shield

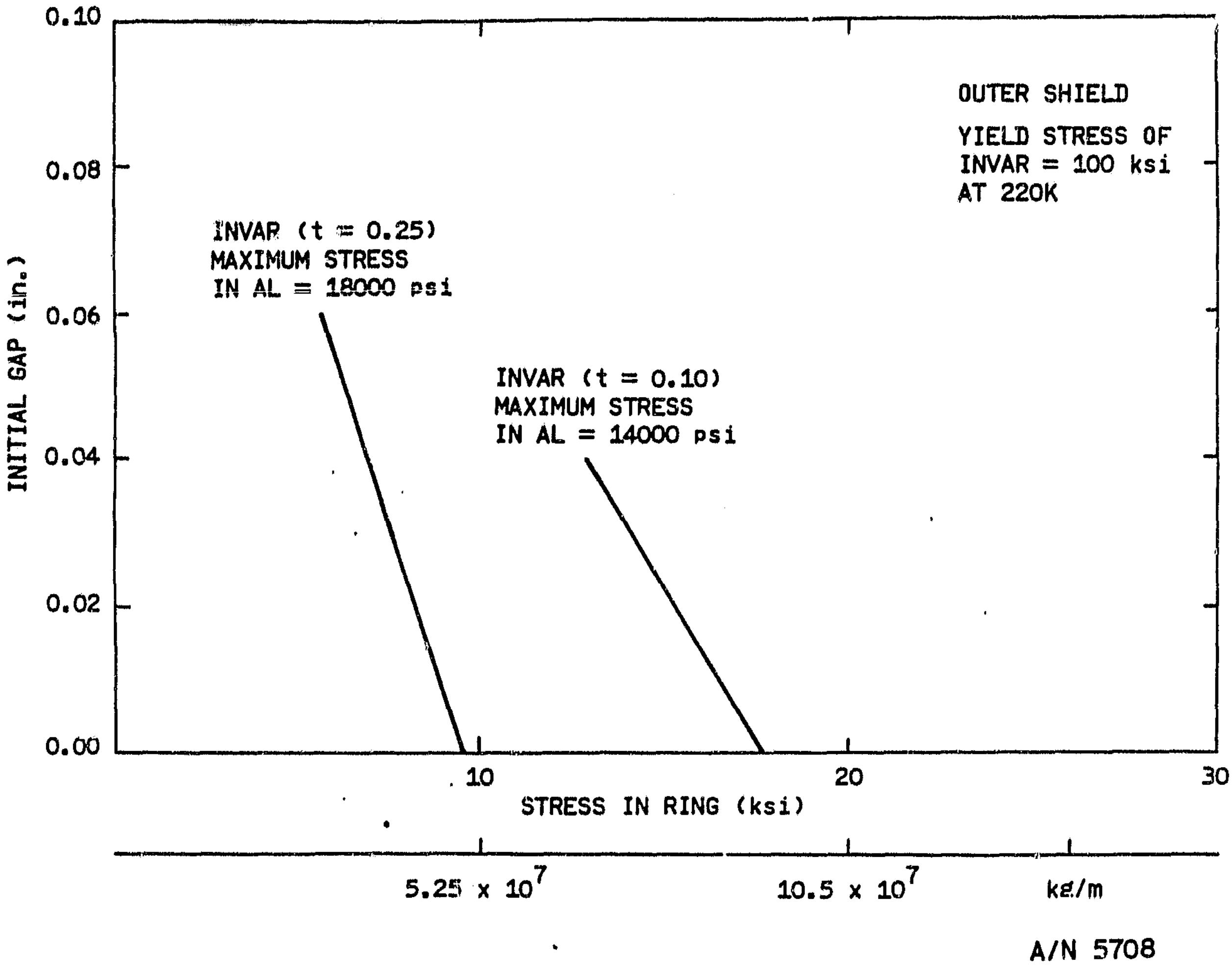

Figure 3-6 Stress From Shrink Fit On Outer Shield

for the thicker Invar rings but they increase for the aluminum. From these charts it can be seen that use of the 0.25 inch thick ring results in a pressure of 6.5 to 28 psi for a nominal gap of 0.030 inches ±0.020 inches.

Figure 3-7 and 3-8 show similar trends for the innermost shields. Other materials could be considered to find an optimum stress/pressure range, but this is sufficient to show feasibility.

The thermal conductivity of rings under pressure is not easily assessed. BASD has run conductivity tests at cryogenic temperatures where many thousand (9,000) pounds were applied to a 1 cm^2 area in order to conduct a few milliwatts. Here we need to conduct several watts. On IRAS, the head shields were riveted to the cylinder shields with perhaps a dozen rivets and the heads cooled to within a fraction of a degree of the cylinder temperature. The heat shrink fit, even at 6.5 psi will certainly provide better conduction than the rivets due to the very large area of contact.

Roundness of the rings and heads does not need to be held to the gap tolerance. A review of figures 3-3 and 3-4 shows guiding tapers three to four times the gap between shields. These tapers could be made larger if needed.

3.3 IMPACT ON CRYOGENIC PERFORMANCE

The baseline SIRTF cryogenic system has an integrated cryogenic tank insulation system and outer shell. The telescope and MIC/Instruments are inserted through the aperture. There is only one radiation path to the warm environment and that is at the aperture. To permit instrument and various component changeout the most likely candidate configuration is through a rear access. We now have two heat paths to the warm surface. The design will be such as to minimize the radiation through the insulation joints but it will not be eliminated and the inner vapor cooled shield will be slightly warmer. Also to provide rigidity to the large vapor cooled shield assembly, supports will be required which will increase the heat leak between shields

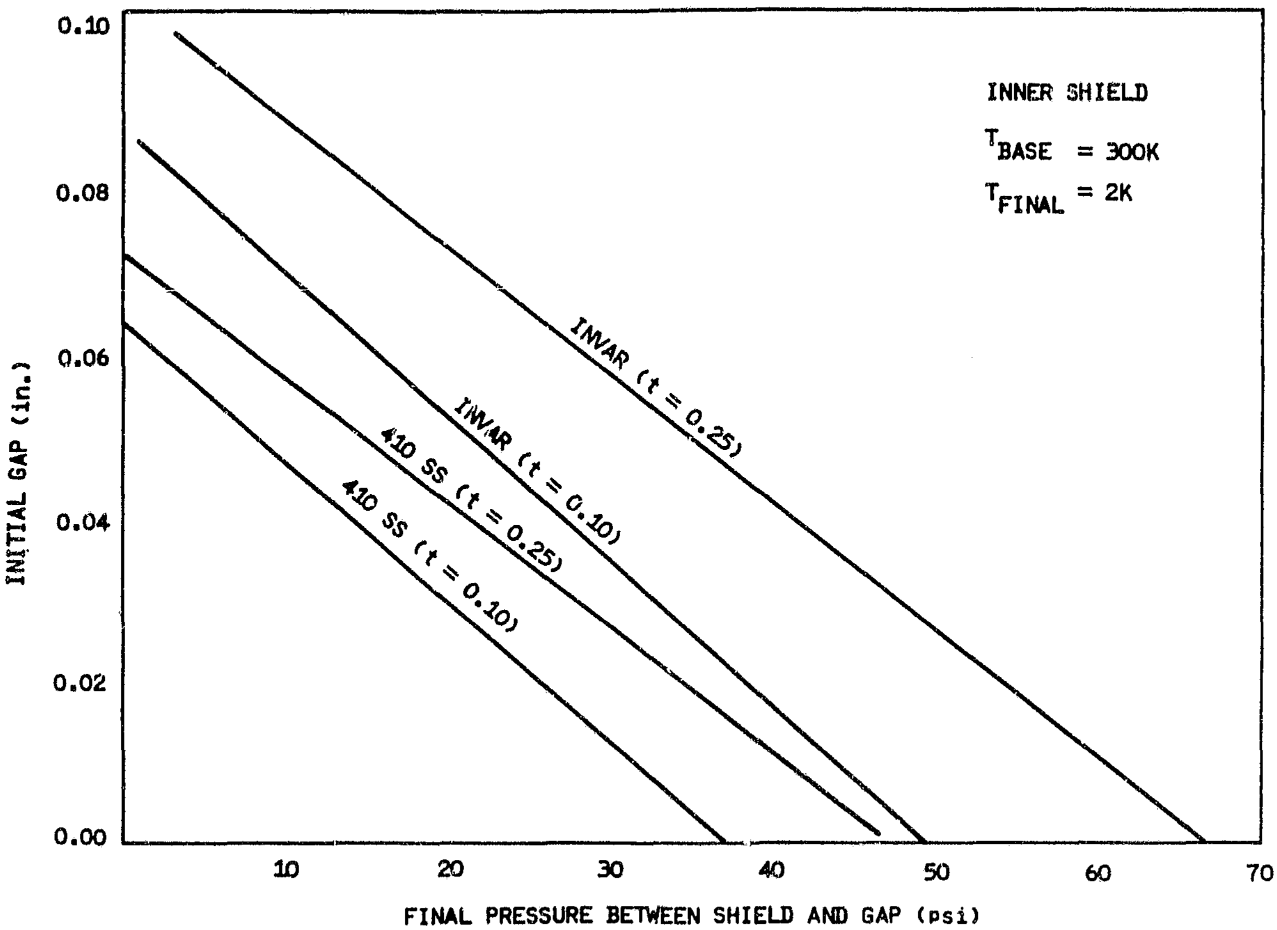

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Figure 3-7 Contact Pressure On Inner Shield

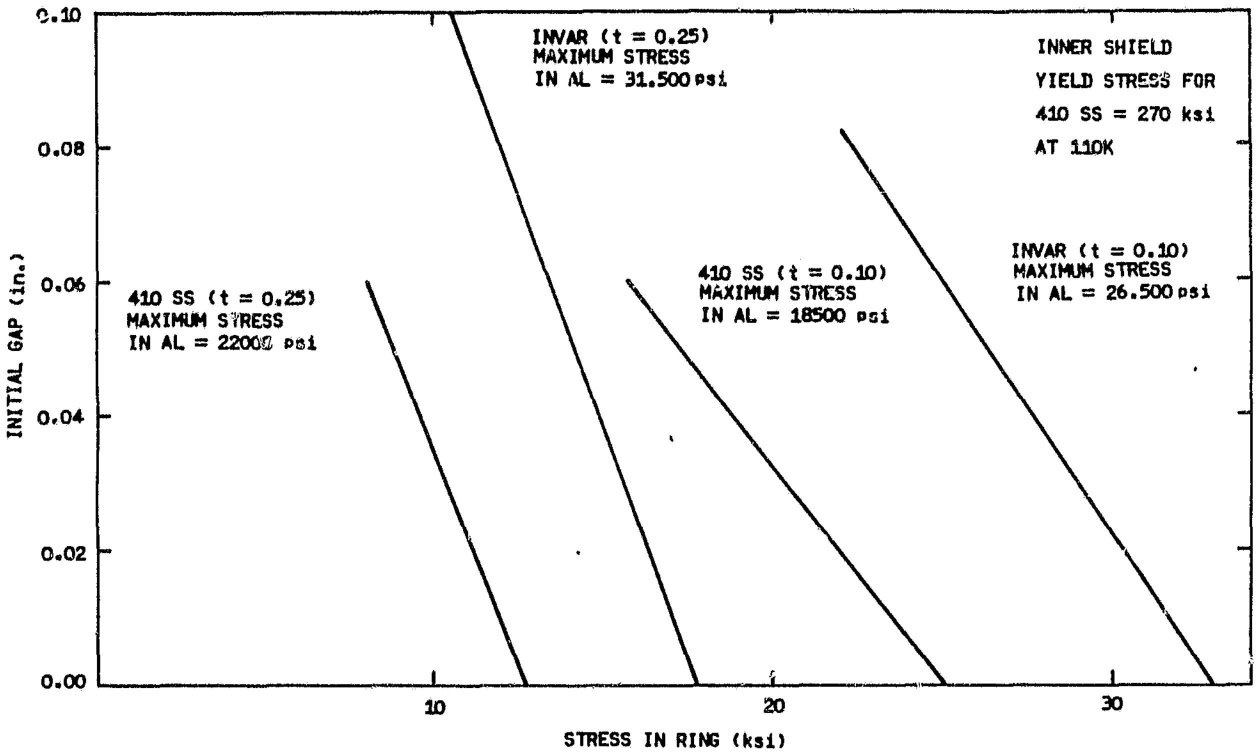

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Figure 3-8 Stress From Shrink Fit On Inner Shield

thereby raising each shield's temperature and causing a small increase in heat leak to the cryogen tank.

The lifetime impact analysis was made using the thermal model developed during the BASD Thermal and Cryogenic Study for SIRTF[1], and so the revisions caused by the rear access can be directly compared to the previous model and study results. The effect of the added heat in the insulation system due to the potential gaps and the vapor cooled shield supports are presented in Table 3-1.

Table 3-1
Instrument Changeout
Lifetime Degradation Effects

GAP (cm)	ΔQ-mW- OVCS (mW)	MVCS	IVCS	VCS Support Type	Δ Life (Years)	Lifetime (Years)
0	0	0	0	-	0	2.6
0.32	739	101	9	-	0.3	2.3
	206	91	18	Concentric Tube, Point Contact	0.2	2.4
Lifetime Including Replenishment Modifications						2.2 years

The net effect of the instrument changeout will be a loss in life of from 0.2 years to an absolute worst case of 0.5 years. By adequate control of the insulation system edges the heat flux through the gaps can be minimized. One could assume that a perfect matchup of edges could be accomplished but with 1/4 mil mylar and net which purposefully has no stiffness this assumption would be somewhat naive. So the trade is whether to close the gap and experience some increased conduction or purposefully allow a slight gap. A 0.5 year degradation estimate for the instrument replacement should be realistically conservative.

3.4 SERVICING FOCAL PLANE INSTRUMENTS

The details of designing the focal plane instrument hardware to accommodate on-orbit changeout can only be worked out as the designs of the instruments and of the facility multiple instrument chamber (MIC) into which they fit are developed. At this point, however, it is important to assess the likely design impacts which could affect the overall system design or performance.

3.4.1 Mechanical Design Impacts

Figure 3-9 shows the one piece end closure fully open and the MIC uncovered. The MIC itself consists of a mounting plate which attaches to the dewar and supports the telescope. Surrounding the instrument cavity is a non-structural photon shield one meter in diameter by one meter long, with a removable cover. The center portion is occupied by the rotating beam splitter and the fine guidance system. Three science instruments are located in the remaining annular space.

The original instrument mounting concept was to cantilever mount them to the mounting plate to a modular set of holes. This was to provide structural mounting as well as a conductive thermal attachment. This concept remains feasible if no other structural support is to be added. At the start of this study there were six candidate instruments occupying the entire annulus and it was difficult to visualize how they would be bolted in place. Now the number is three - two at 60° and one at 90°, and they are readily bolted to the mounting plate using external flanges.

A nonredundant, statically determinant mounting method is required so that any distortions of the mounting plate do not stress or distort the instruments. Mounting on three parallel pads with three bolts very nearly provides this requirement. Two very accurate positioning pins adjacent to two bolts on opposite flanges are required. One of the pins is round and the other is diamond shape to control rotation about the round pin without overly constraining the space between them.

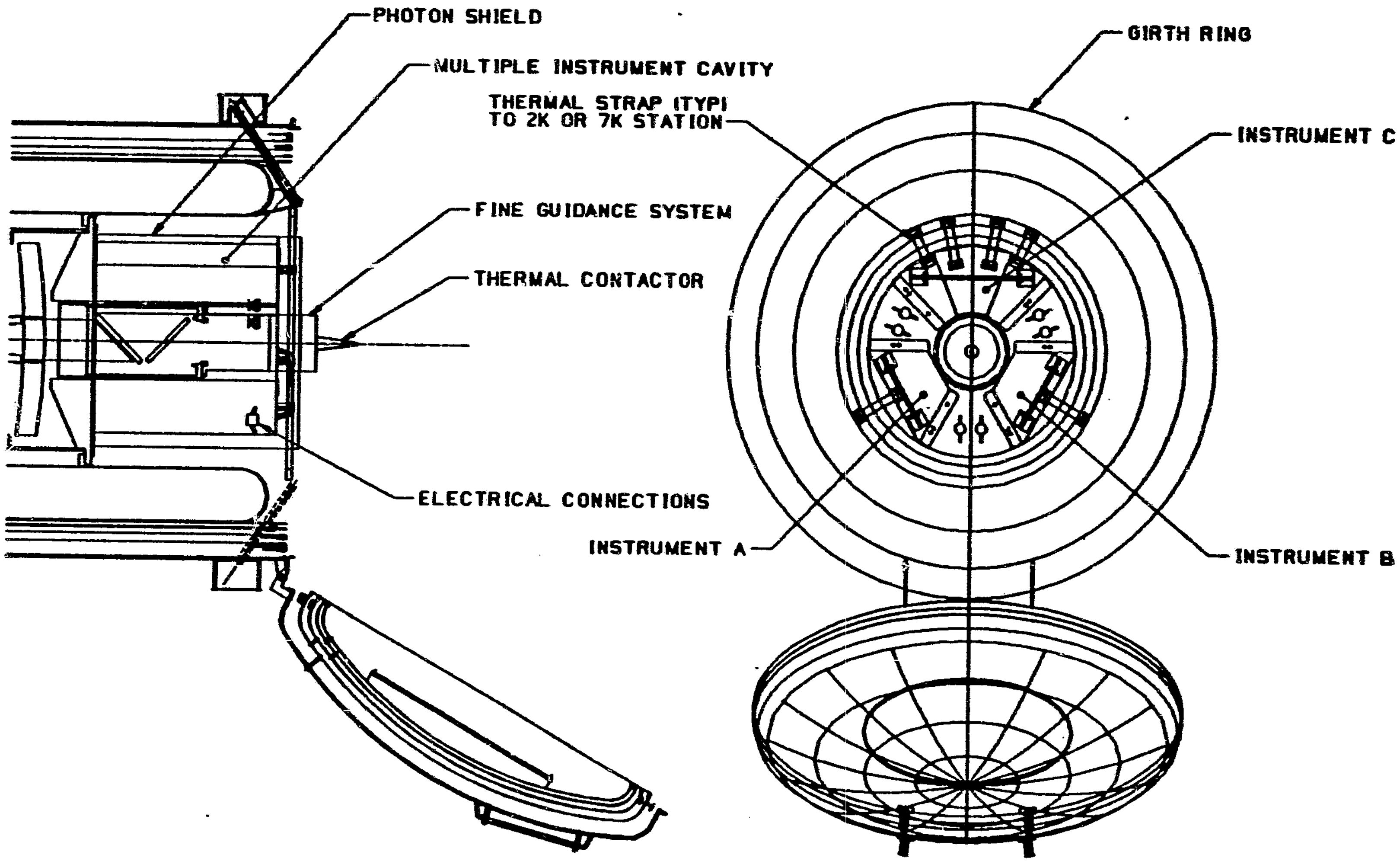

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Figure 3-9 Instrument Rear Access

3.4.2 Other Design Impacts

On Orbit Cooldown

In some cases the instrument focal plane assemblies will be thermally isolated from the rest of the instrument because of elevated temperature requirements. This will not interfere with the on orbit cooldown of the facility, but may delay instrument check out by several hours. The instrument check out would be required prior to SIRTF being released.

Temperature differences between the MIC and the new instruments will need to be minimized prior to changeout so as to insure alignment when cooled down to a uniform 2K. Heaters on the MIC will probably be required.

Super-Cooling

An adiabatic demagnetization refrigerator (ADR) could be included an instrument. All thermal interfaces of the ADR will be the responsibility of the instrument. A high current lead will be provided by the facility at the 7K station. This electrical interface connection will need to be low electrical resistance so as to preclude joule heating and a loss of super conductivity.

Helium-3 connection to the instrument (if needed) could be a blind probe sticking out of the instrument. The connection is made when the instrument is locked down. Providing a low impedance vent for an open cycle system could be a real problem. This question has not been addressed.

Human Factors

Normally the MIC and the instruments would be painted black so as to minimize stray light problems. Changeout of black instruments inside a black cavity while in a space suit will be next to impossible. One possibility is to enclose the optic train so as to permit the instruments to be painted

white and interfaces to be adequately marked or color coded. This optics train cover will also serve to protect the fragile optics.

In order to keep the change out process simple, instruments should be limited to one black box at the MIC and one black box outside the instrument. Electrical interface connections should be minimized and plumbing connections should be an integral part of the box mounting.

Guide Rails

Guide rails will be required for on-orbit instrument removal and insertion. Since they are not essential for ground work, they can be incorporated in the non-structural photon shield, as shown in Figure 3-10. There will be some rubbing contact, so one surface should be Delrin 500 (Acetal) as is used for the ST guide rails.

Thermal Strapping

If there were to be no instrument changeout, the instruments could be bolted in place in this manner with indium or gold foil to enhance thermal conductivity. However, any contamination (i.e., velcro, body oils) of this instrument-MIC interface during change out will affect alignment and thermal conductivity. Thus, instrument changeout requires a somewhat different approach while maintaining the main mounting features.

The indium or gold foil cannot be used at the structural attach pads. If an instrument is removed and pieces of foil stick to the pads, alignment of the next instrument would be affected. Also, the gasket residue will preclude a good thermal interface for the new instruments. Instead, thermal strapping directly from the helium tank will be used for the 2K control. The MIC could provide multiple attach points near each instrument with a clean one being used each time an instrument is changed out. These attach points must be accessible to the astronaut at the back of the instrument, which may complicate the instrument thermal management.

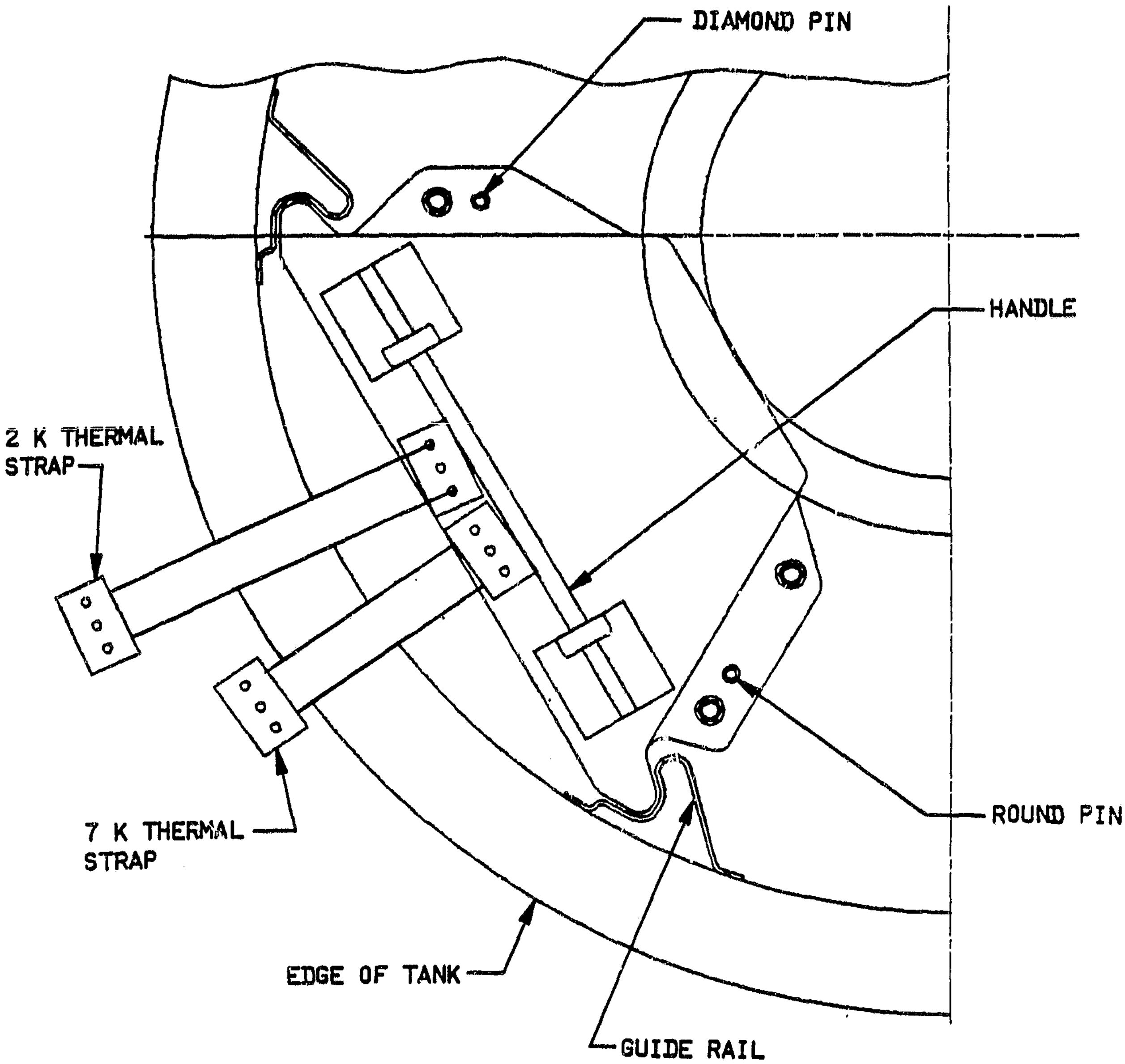

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Figure 3-10 Instrument Mounting

Handles

Astronaut rated handles must be mounted on the rear of each instrument. Clearance must be provided for gloved hands, and this either reduces the allowable instrument length, or the MIC must be extended in length to accommodate the handles. Astronaut handles impose a structural load of 30 pounds in all directions. This imposes a design requirement on all experiments.

Round Corners

For crew member safety, all corners exposed to possible contact must be rounded. All edges and corners of the instruments must be rounded, as well as all exposed edges and corners of SIRTF in the vicinity of the instruments.

Electrical Connectors

Special EVA rated connectors are required for changeout. They require more space than conventional connectors but this does not create a problem with only three instrument occupying the MIC. However, the harness and cable routing must be considerably different for changeout versus no changeout. The connectors must be accessible from the rear of the MIC and there must be hundreds of spare wires to cover all contingencies for second generation instruments. If a manual astronaut operation is necessary, then one cold electrical connection per instrument should be the design goal keeping in mind that the shielding of the different signals is important. An alternate approach would be to have the electrical interface connection a rigid probe. The connection is automatically made when the instrument box is installed.

SUMMARY OF CHANGEOUT IMPACTS

ITEM	IMPACT ON INSTR	IMPACT ON SIRTF
Guide Rails	Required	Required
Thermal Strapping	Required	Required
Handles	Required	Required
Round Corners	Required	Some
Electrical Connectors	Little	None
Wiring	None	Increased

3.5 SERVICING OTHER COLD MECHANISMS

The fine guidance sensor (FGS), rotating beam splitter, and the chopping secondary mirror are essentially undefined at this time. However, their locations are known, and some assessment on their mounting and the impact of changeout can be made. They all must be hard mounted and locked for launch loads, and they all will have electrical leads which must join the main harness cable to exit the dewar through the vacuum shell. However, they will most likely all have connectors to facilitate assembly, checkout and ground testing. Changeout on orbit is then primarily a question of access on orbit.

Fine Guidance Sensor

This has been depicted as mounted on a cylindrical structure surrounding the beam splitter and supported from the MIC mounting plate. However, the telescope beam must pass through the cylinder so it can only use approximately three 60° sectors between experiments. Mounting could be the same as for the instruments, and access would be identical through the one piece end cover for changeout. An alternate mounting is to support the FGS on spiders attached to the MIC plate between instruments. This would provide better access for crew members since it could be removed from the spider.

Rotating Beam Splitter

This is directly mounted on the MIC plate. It can be flange mounted between instruments. The FGS would necessarily have to be removed in order to remove the rotating beam splitter.

Cryogen Valves

All of the valves can be located on the rear of the cryogen tank where they are directly accessible through the one piece end cover. The valves are motor driven and it is not anticipated that they will be removed from the plumbing lines. At most, only the motors and gear heads would be changed.

Chopping Secondary Mirror

The chopping secondary mirror is only accessible through the sun shade and front aperture. It would be too hazardous to insert any part of the astronaut's suit inside the baffles, so he could only get his hands to within 1.6 meters of the mounting plane. A special tool would be required to extract and insert the assembly. Also the assembly will have to be keyed and have a blind connector. An alternative would be to chop with an articulated mirror located in the MIC. This would make on-orbit replacement easier, but would constitute a significant departure from the baseline. The scientific impact would need to be studied.

Conclusion

The mechanisms listed above should have redundant motor windings and not be considered primary ORUs. However, they should be designed with changeout in mind.

Section 4
MISSION ANALYSIS

This section describes the operational aspects of in-orbit cryogen replenishment and instrument changeout of the SIRTF. It is intended to provide the following:

- Mission scenarios for performing the cryogen replenishment and instrument changeout of SIRTF on both Space Station and Shuttle.
- The operational sequences and timelines associated with these scenarios.
- The interfaces, operational constraints, and requirements of the hardware elements of the missions.
- The impacts of human interface including EVA and safety requirements.
- The impact of performing these operations on Space Station.

A detailed summary of the Space Station based mission discussion in this section appears in Appendix A as a stand alone document. It focuses specifically on the Space Station activities, with mention of the Shuttle only as a means of transportation of the ASE to and from the Station.

4.1 SERVICING MISSION OPTIONS FOR SIRTF

To achieve the mission lifetime objectives and to support the evolving needs of the astronomical community, it will be necessary to provide in-orbit servicing operations on SIRTF that will include the following:

- Cryogen replenishment- The lifetime of the liquid helium supply of the SIRTF dewar is currently baselined to be two years. In

order to extend the lifetime of the facility to the desired ten to fifteen years, it will be necessary to periodically replenish the liquid helium system. This will be performed either on Space Station or on Shuttle and requires a replenishment supply dewar of 5000 - 11000 liter capacity.

- Instrument changeout- It will be highly desirable to provide the capability of changing out focal plane instruments in order to recover from the failure of an instrument, to upgrade the instruments to take advantages of improved technologies, or to change the type of instruments and the capabilities of the facility to meet changing requirements of the science community.

- Facility repair- To achieve a ten year mission lifetime, it would be prudent to anticipated problems or failures in mission-critical mechanisms and to build into the facility a capability of performing in-orbit replacement or repair. For the purposes of our discussions, repair operations are considered a subset of the instrument changeout mission.

Top level Servicing Options

The various options for SIRTF servicing are shown in Figure 4-1. For the 28.5 degree inclination orbit SIRTF may be mounted on Space Station or, for the 900 km altitude orbit, be based on a dedicated satellite, a station co-orbiting platform, or a leased platform. The satellite or platform based SIRTF can, in turn, be serviced by one of three approaches:

- SIRTF descends to Space Station orbit and is serviced at Space Station,

- SIRTF descends and is serviced on the Orbiter,

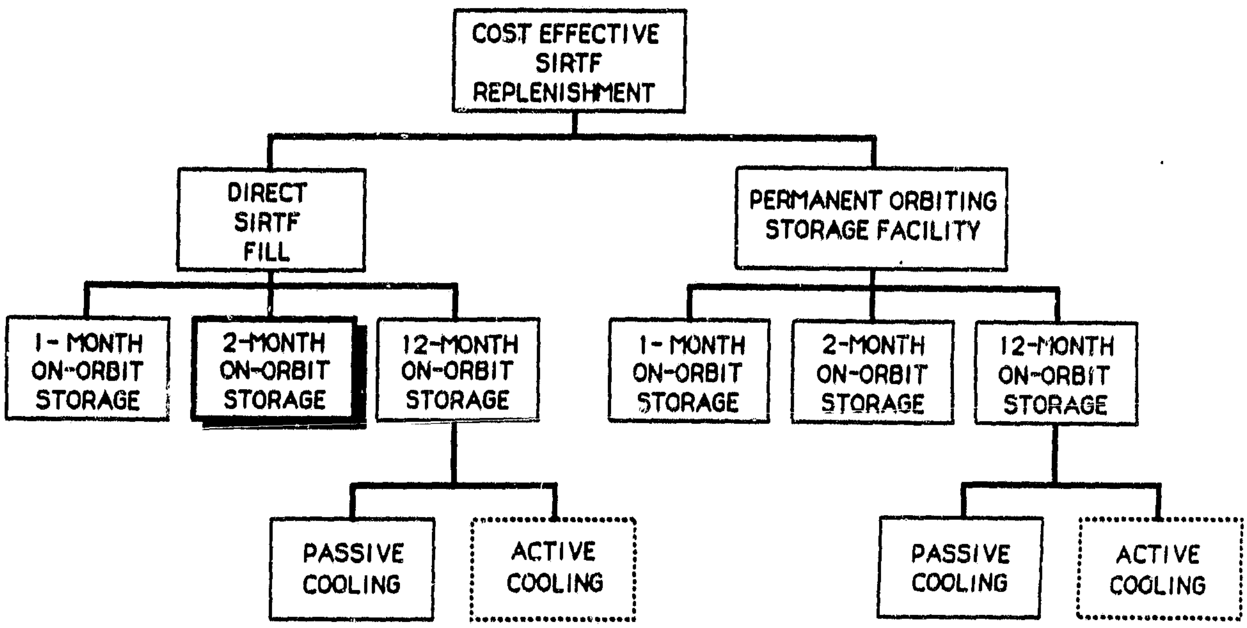

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Figure 4-1 Replenishment Mission Options

- The OMV ascends to SIRTF orbit with the ASE and the replenishment operation is performed by a teleoperated robotic system.

Since we are baselining man-tended transfer operations, we will not consider the third option of using a teleoperated system. For the Orbiter based servicing we discuss the basic cryogen replenishment operations in Section 4.3.2 and the instrument changeout operations with subsequent cryogen replenishment in Section 4.4.1.

For the station-based operations, we discuss the detail scenarios for performing the replenishment on SIRTF berthed on the station in Section 4.4.2. A summary of the implications of performing the instrument changeout on station are discussed in Section 4.4.3. The detailed timelines and operational sequences, however, duplicate much of what is presented in the earlier sections and hence are relegated to Appendix A. Since the proximity zone servicing from Space Systems also relies on teleoperated systems, it is not discussed.

4.2 SERVICE MISSION ELEMENTS

Before presenting the mission scenarios and timelines for the cryogen replenishment and instrument changeout operations, a brief description of the hardware and operational elements of those missions is in order.

This section summarizes the parts played by these elements in the missions. In addition, there are some general considerations, common to all of the variations of the missions that are discussed in the last part of this section. These include the constraints imposed by EVAs, safety requirements and contamination control concerns.

4.2.1 Hardware Elements

The following discussion describes the role played by the various hardware elements in the mission scenarios.

Shuttle

The Shuttle plays a role in all the servicing scenarios. For Space Station-based servicing the Shuttle delivers the ASE to the Station prior to servicing and returns the depleted dewar sometime after the operations are complete. For Orbiter-based servicing, it delivers the OMV to low earth orbit (LEO), serves as the site of all the servicing operations, and provides the means for contingency return of SIRTF in event of problems. The following standard hardware elements are also involved in the mission:

- Standard Orbiter Remote Manipulator System (RMS) -
  - Deploys and stows the OMV
  - Demates and mates the OMV and SIRTF
  - Positions SIRTF for capture by the A frame latches
  - Positions OMV/SIRTF for post-servicing deployment
  - Positions EVA crewman and Orbital Replacement Units (ORUs) for changeout operations.

- A Cradle -
  - Supports SIRTF in cargo bay during servicing operations
  - Modified to provide storage of ORU's and tools during launch and operations.
  - Provides intermediate storage for instruments during changeout.
  - Provides storage for "old" instruments during deorbit and landing.

- Manipulator Foot Restraint (MFR)-
  - Restrains EVA crewman, tools, and ORU's during changeout operations.

Space Station

The Space Station is the alternative site for the cryogen replenishment and/or the instrument changeout operations. The ASE dewar would be stored here for up to two months prior to the replenishment and in the interim could service several smaller experiments. The OMV used to retrieve SIRTF would be normally based at the Station and would require refueling on Station before returning SIRTF to an operational orbit. The configuration and facilities assumed for Station are taken from JSC-19989, "Space Station Reference Configuration Description".

Orbital Maneuvering Vehicle

The OMV is used to retrieve SIRTF to the Orbiter and to reboost SIRTF to its operational orbital altitude following the servicing mission. The OMV for the Orbiter based-operations will be transported to LEO by the Shuttle. The OMV for the Space Station-based operations will be one of the Station-based OMV's. The concern for contamination of the SIRTF during OMV proximity operation is somewhat relieved by the recently proposed use of the cold gas RCS. However, the SIRTF aperture closeout mechanism is still considered necessary to minimize contamination of the SIRTF telescope.

The orbit transfer capability of the OMV is shown in Figure 4-2. The configuration, capabilities, and transfer times for the OMV are based on the January, 1985 revision of the MSFC OMV Preliminary Definition Study.

Airborne Support Equipment

The ASE for the changeout and replenishment operations is described in Section 2.3. The role of the ASE in the operations is summarized below :

- Provides helium (and hydrogen) supply storage,
- Provides transfer lines , pumping mechanism and pump control,
- Provides supply dewar monitoring and control,

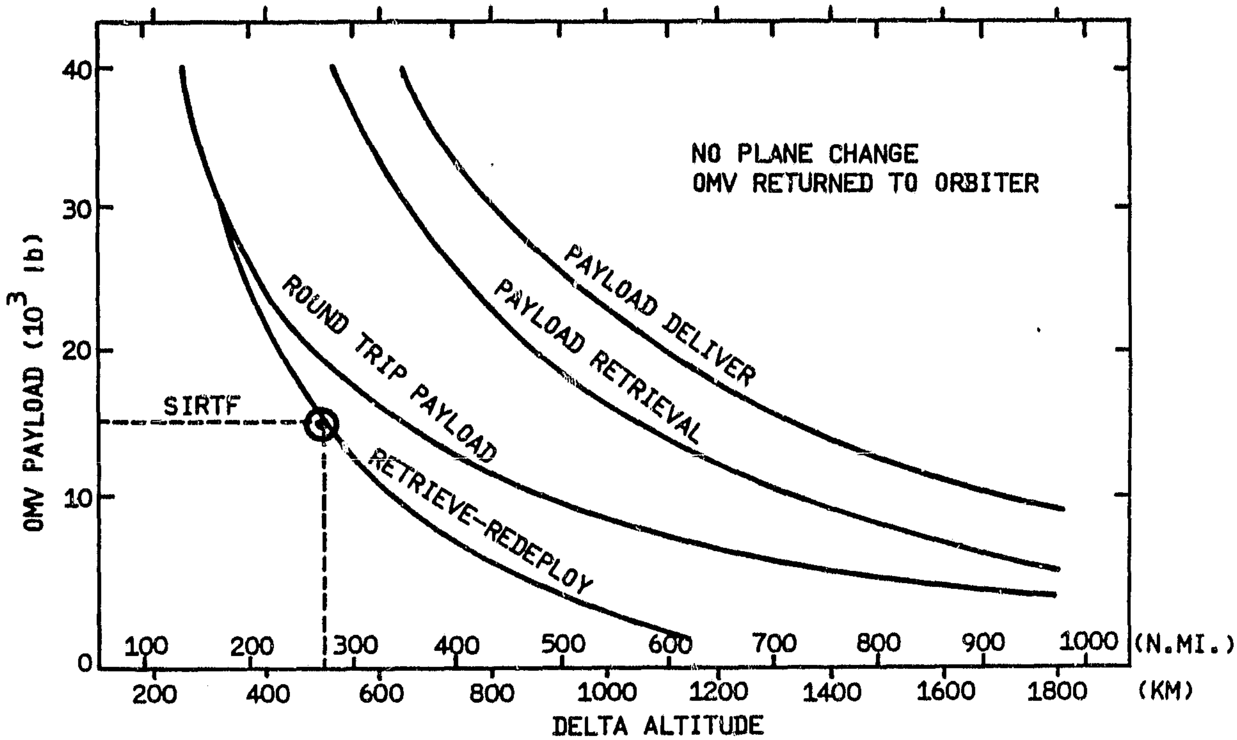

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Figure 4-2 OMV LEO Performance

- Provides SIRTF dewar monitoring and control,
- Provides the data and power interface to Station or the Orbiter, and
- Provides formatted data to Orbiter or Station interface for telemetry to ground.

SIRTF

The modifications to SIRTF required for replenishment and instrument changeout are discussed in Section 2.2. These are summarized below:

- Plumbing interface for EVA installation of transfer line,

- Electrical umbilical interface to permit external valve control and sensor monitoring by ASE,

- Dewar modifications as described in Section 3 to allow instrument changeout,

- Instrument interfaces conforming to the changeout requirements, and

- Internal thermal interfaces compatible with the cooldown and thermal stabilization times presented in Section 4.3.

4.2.2 Operational Elements

Ground operations

PRELAUNCH- Whether or not the ASE dewar will be delivered to KSC filled or warm will depend on the details of economics of helium loss versus transportation costs. However, under normal circumstances, there will be two topoff operations for the ASE dewar prior to launch. The first would occur

in the Orbiter Processing Facility (OPF) after the Dewar has been integrated into the Orbiter bay. The second topoff would occur in the Rotating Service Structure at the pad. This second topoff will require on the order of 1500 liters of helium to be available in a GSE supply dewar. Because of physical limitations in the service structure , special provisions for 1500-2000 liter GSE dewar may have to be made.

POST-LANDING- There are no special requirements associated with the post-landing operations unless it is necessary to return SIRTF to earth in the event of a problem. In this case, a suitable environmentally controlled transporter would be required.

FLIGHT OPERATIONS

EVA- The EVA tasks are shown in Table 4-1.

IVA- Intravehicular activities by crew are assumed for the following operations:

- RMS (or MRMS) operation for
  - Deploy and stow of the OMV,
  - Demate and mate of the OMV and SIRTF,
  - Positioning SIRTF for capture by the A frame latches,
  - Positioning OMV/SIRTF for post-servicing deployment, and
  - Positioning EVA crewman and ORU's for changeout operations.

- Monitoring and operation of the command console during ASE and SIRTF dewar checkout, leak check operations and initiation of transfer operation.

POCC- The use of the JSC Payload Operation Control Center is assumed. It would be staffed with cryogen transfer and facility specialists who would participate in the following operations:

Table 4-1
SIRTF EVA TASKS

Task	Replenishment mission	Changeout mission
Transfer line		
• Mate	P	P
• Demate	P	P
SIRTF Umbilical		
• Mate	P	P
• Demate	P	P
Sunshade Cover		
• Installation	P	P
• Removal	P	P
Dewar Access		
• Open	N/A	P
• Close	N/A	P
ORU changeout	N/A	P
Solar Array		
• Latch	C	C
• Unlatch	C	C
• Storage	C	C
• Jettison	C	C
Antenna		
• Latch	C	C
• Unlatch	C	C
• Storage	C	C
• Jettison	C	C

N/A = Not applicable to that mission
P = Planned
C = Contingency task, unsceduled

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- Monitor telemetered data during health checks of both dewars,
- Maintain voice link with crew during setup and transfer operations,
- Control transfer operation during crew rest periods, and
- Provide technical assistance in event of any abnormality in operation.

CONTINGENCY- In the event of a failure of any of a variety of mechanisms that might endanger the success of the mission or safe return of the Orbiter and crew it is necessary to provide for the following operations :

- Manual backup for deployment and retraction of solar arrays, antennas, trunnions and A frame mounting interface;
- Manual jettison of solar arrays, antennas;
- Installation of SIRTF in the Orbiter bay for safe return; and
- Contingency EVA to support manual operations.

In the event of an aborted mission that requires the return of SIRTF to earth it will be necessary to either 1) provide for expulsion of the helium from the main tanks or 2) install a temporary pressure dome to substitute for the aperture cover.

If the main tanks of SIRTF are full at the time the decision to abort is made, it will take 6 to 8 hours to dump the tanks and 30 hours to warm the SIRTF telescope system to 300K. The dewar insulation system would still be cold at this time and atmospheric condensation would contaminate the MLI. The risk of contaminating MLI might be an acceptable option in the event of

an abort compared to the difficulty of installing a reliable pressure dome over the aperture. These alternatives will require a system level trade during the early phases of the replenishment program.

4.2.3 General Mission Considerations

The constraints imposed by the requirements of EVA compatibility, safety and contamination control are essentially the same regardless of the mission scenario. The following discussion summarizes these requirements.

EVA Compatibility

The design requirements for EVA compatibility specified for STS operations in JSC-10615 will probably be comparable to those demanded by Space Station operations, so we have used these as a basis for this discussion. When considering a total EVA mission the ASE and SIRTF designs should address the following:

- Airlock to payload access corridor,
- Translation aids to the worksite,
- Cargo transfer requirements,
- Crew and equipment safety,
- Restraint provisions at the worksite,
- Visibility and lighting requirements,
- Working volume requirements,
- Extravehicular (EV) glove interface, and
- EVA tool design.

In addition, mission planning must account for the six hour limit on EVA duration and the four hour preparation required for each EVA. A nominal STS mission includes provisions for two 2-person EVA's with one contingency EVA for emergency purposes only. Additional EVA's are possible if necessary but require additional EVA kits. Rather than repeat the lengthy requirements

stated in JSC-10615, we will highlight the major points that affect the SIRTF and ASE designs or the changeout/replenishment operations.

- Airlock to payload access- The payload must allow egress from the Orbiter airlock. A 48 inch clear envelope at the forward part of the bay is reserved to permit outer hatch operation and egress.

- Crew and safety requirements- These are discussed on the safety section.

- Restraint provisions at the work site- Handholds and foot restraints must be provided by the payload to provide the crew-member with a reaction point against the forces or torques associated with any mechanical activity. This is considered to be the single most limiting factor of all EVA elements, often causing crew fatigue and early termination of the EVA.

- Glove interface and equipment design- The transfer line bayonet connections and electrical connectors for the umbilical must be compatible with gloved hand operation. Installation and removal torques should not exceed 15 N-m (11 ft-lb). They should be designed to allow one-hand operation , allowing the other hand to be free for position management.

- Number of EVA's- The cryogen replenishment operations require two each two-person EVA's. The instrument changeout operation requires three EVA's and provisions for a fourth contingency EVA is recommended.

<u>Safety</u>

The safety requirements for the ASE dewar and the EVA operations are governed by NHB 1700.7 and JSC-10615 respectively. NHB 1700.7 categorizes

the ASE dewar as a cryogenic pressure vessel and curiously, the cryogen as a propellant. This has the following consequences:

- As a pressure vessel, the ASE dewar is considered a fracture critical item and must meet fracture critical design and testing requirements. Although this has some cost impact, it is the same requirement that has been successfully met by COBE.

- In the case of a catastrophic loss of guard vacuum of the ASE dewar, a significant heat load would be applied to the helium tank. The system must be capable of relieving the increased pressure in the tank without rupturing. The COBE power was able to meet this requirement by analysis, showing that a burst disc would open a vent line of adequate conductance to prevent overpressurization. However, that dewar could vent the cold helium into the Orbiter bay without lowering the average temperature of the bay enough to affect any electronics. This may not be the case with the 5300 or 11000 liter ASE dewar. Provisions for overboard dumping of the cryogen may be required.

- Valves cannot be actuated accidentally- This can be accommodated by good electrical design practice and by requiring a minimum of two commands, "arm" and "actuate", or serial manual switching and command combinations for valve actuation.

- Double redundancy on valve opening and triple redundancy on valve closure is required- This is a consequence of the cryogen being classified as a "propellant" by NHB 1700.7. Given that helium is chemically inert and has a relatively low heat capacity, it may be possible to get this requirement modified. Triple redundancy implies a very complex design of the dewar plumbing scheme and the transfer line. This requirement would apply to the transfer line in order to meet the requirement to protect the crew members from any fluid hazard such as spillage after disconnect. We

believe that this requirement was not applied to the COBE dewar because no crew members are involved with valve operations.

The crew and equipment safety requirements related to EVA are given by JSC-10615.

- No single failure or operator error shall result in damage to equipment or in the use of contingency or emergency procedures.

- No two failures and/or operator errors shall result in personnel injury, loss of life, or prevent the safe return of the Orbiter vehicle.

- The payload structure must be compatible with the EV crewmember's life support system and space suit components. Hence there can be no protrusions or sharp edges that might cut, abrade, puncture, or otherwise damage a suit. The detail criteria for this requirement are given in the referenced JSC document.

- It is the payload's responsibility to provide inherent self-protection or define crew operational constraints to prevent contamination from the EMU discharges of water and oxygen.

The first two requirements necessitate manual backup modes to deployment operations and the capability of manual jettison of the SIRTF. System redundancy and command redundancy will also be required. The extent of the redundancy would be determined during the initial system design. The third requirement would be imposed as a design requirement on the ASE, SIRTF, and the instruments involved in the changeout operation. The requirement is verified by inspection. The fourth requirement is discussed in the following section.

Contamination Control

The contamination control requirements for SIRTF are difficult to meet under the best of circumstances. Neither the environment of the Orbiter nor of the Space Station can be expected to be benign, and specific measures will be required to prevent severe contamination of the SIRTF optics. The major sources of contamination that will have to be contended with are:

- Orbiter
  - Outgassing products on the order of 10^{-11} g/cm^2/s of high molecular weight and water.
  - Frequent water venting, RCS firings
  - A source of large particles, on the order of Level 750 with a distribution strongly biased toward larger particles.

- OMV- The OMV will use a hydrazine bipropellant propulsion system. The potential for contamination production is high but not yet characterized. A recent modification, however, is to use compressed gas for the RCS which is not a threat.

- Space Station- Although uncharacterized at the present, the station will probably be similar to the Orbiter except bigger and hence worse. The size is an advantage however, since it will permit the use of large, protected bays for operations such as the replenishment or changeout. The bays will be easier to control than the Orbiter environment.

- EMU
  - The space suit sublimates 0.77 kg/hr of water.
  - The suit is known to be a significant source of particle contamination but we are unaware of any quantitative characterization.

The space suits present the worst problem for instrument changeout because of the unavoidably close proximity of the contaminant source to the sensitive elements, the instruments themselves. As mentioned earlier, the use of the EMU precludes the possibility of performing a cold instrument changeout.

The final solution to the contamination problems of servicing SIRTF will require detailed analysis and planning and is well beyond the scope of this study. However we have some strong recommendations that we have implemented in our design and mission planning.

- Aperture Cover. An aperture closeout shutter or cover is absolutely required to protect the telescope optics during all operations. The design of the cover is discussed in section 2.2.3. The cover must be closed remotely prior to the initial OMV rendezvous, and not opened until the facility has been serviced and returned to operational orbit and the OMV has departed. The only exception to this would be if the telescope secondary mirror assembly required servicing, and then only if the system has been warmed to 300K.

- Sunshade Heater. The sunshade inner cone should be warmed by heaters to above 270K prior to the OMV rendezvous. This temperature should be maintained throughout all operations if possible.

- Sunshade Cover. A sunshade cover should be installed over the opening of the sunshade as early as possible after station or Orbiter rendezvous. This cover is primarily to protect against particle contamination of the low-scatter inner cone surface. The cover should remain in place until just prior to SIRTF/OMV deployment. If installed by EVA, the cover could be a collapsible plastic "shower cap" that would be stretched across the sunshade aperture. If the RMS is used for a remote

installation, then the cap would have to be structurally compatible with the grapple fixture. A remotely operable cover that could be closed before rendezvous with the OMV would be highly desirable, and should be explored.

- Servicing Bay. Operations on Space Station must take place in a low contamination bay, shroud, or tent. An equivalent to a Level 300 environment would be desirable. Surface particle contamination on the SIRTF represents a source of large particles that can be ejected by meteoroid impacts and enter the telescope field-of-view.

There is no immediate solution to the contamination problems associated with the EMU except perhaps an external covering of the suit and vent ducts to control water dumps. This implies a redesign of the suit itself, which is beyond the scope of this study.

4.3 CRYOGEN REPLENISHMENT OPERATIONS

In this section we discuss the cryogen replenishment mission as envisioned for both the Shuttle and Space Station. For both cases, we describe the assumptions used that are unique to the mission, an overall mission scenario, and the general hardware configurations and interfaces. A detailed discussion of the operational sequence and resulting timelines for both sets of initial conditions, filling a 2K or a 150K SIRTF, is also presented.

4.3.1 Assumptions Used

In addition to those described in Section 4.2, there are a set of assumptions used that are common to the operational plans and timelines for all the activities that involved transfer of helium to SIRTF. These are:

- The ASE equipment used would be that baselined in Section 2.

- All connections of transfer lines, electrical interconnects and installation of protective covers for SIRTF would be performed manually during EVA. This has special significance for instrument changeout on Shuttle as discussed in Section 4.4.

- The times incorporated into the schedules for cooldown of a warm SIRTF and transfer of liquid helium are the same for all operations regardless of the site where the operation takes place. The only variations in the schedule are based on whether or not the SIRTF starts warm.

The detailed sequence and times for the cooldown and transfer process are shown in Figure 4-3. These data are based on the analysis discussed in Section 2.4.1. It is assumed that during the cooldown and transfer operations, there will be adequate telemetry links to the Payload Operations Control Center such that the transfer can be monitored and controlled during crew rest periods or during other crew activities. Therefore the transfer operation will continue uninterrupted from the time that helium starts leaving the supply dewar, either for cooldown or transfer, until the SIRTF is full and stabilized.

4.3.2 Shuttle-based Replenishment Operations

For the Shuttle-based missions, the capability and capacity of the Orbiter is assumed to be as defined in Volume XIV of JSC 07700. No additional capabilities or future enhancements were assumed except for the existence of the OMV. We assumed that it was desirable to minimize occupied bay space and mission duration for cost reasons.

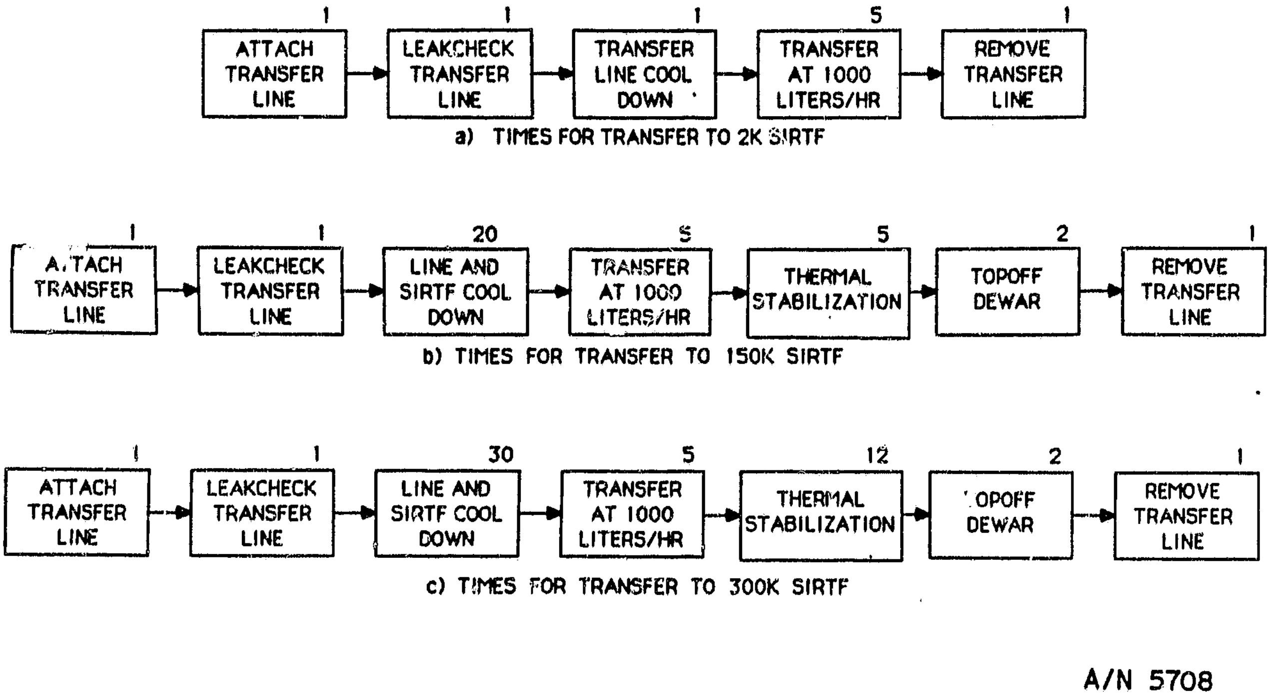

Figure 4-3 Timeline Options for SIRTF Transfer

Mission Scenario

The top level scenario for the Shuttle-based replenishment operation is shown in Figure 4-4. The Shuttle is launched into a 28.5 degree inclination 400 km orbit carrying the ASE equipment and an OMV. 400 km is about the maximum altitude achievable without an additional Orbital Maneuvering Subsystem (OMS) kit. The total weight of the OMV and the ASE is well under the 25,000 lb limit for Shuttle delivery to this altitude so from at least the point of view of deliverable mass capacity, this need not be a dedicated mission. Once at altitude, the OMV is deployed and boosts to SIRTF's 900 km orbit. The SIRTF and OMV return to the Orbiter and are captured by the RMS.

Options for capture technique are shown in Figure 4-5. In one case, the OMV and SIRTF detach and the OMV is stowed by the RMS under the eventual working area for the SIRTF. Then the RMS grabs the SIRTF and sets it on the servicing cradle. This configuration minimizes the bay length occupied by the hardware dedicated to this operation. The second technique places the OMV/SIRTF pair in the SIRTF cradle before separating the two. The second option reduces the time of the stowing operation and the additional attitude trim maneuvers by the Orbiter. This presents a slightly lower contamination risk to SIRTF.

The cryogen transfer is performed. The OMV and SIRTF are recoupled in the reverse manner of the stowing operation and the pair are deployed and boost back to SIRTF's operating orbit. The OMV returns to the Shuttle, is stowed and the Shuttle returns to earth. In this scenario, neither weight limitations nor bay space restrictions necessitate that this be a dedicated mission.

Hardware Configuration

A sketch of the ASE, OMV and the SIRTF as they might be positioned in the Orbiter bay is shown in Figure 4-6. The SIRTF is shown mounted towards the

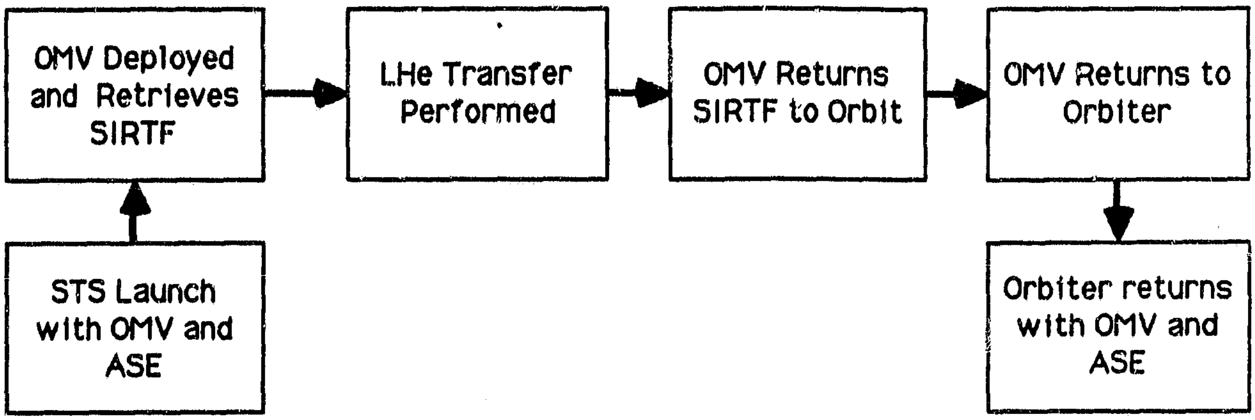

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Figure 4-4 Scenario for Shuttle-Based Replenishment

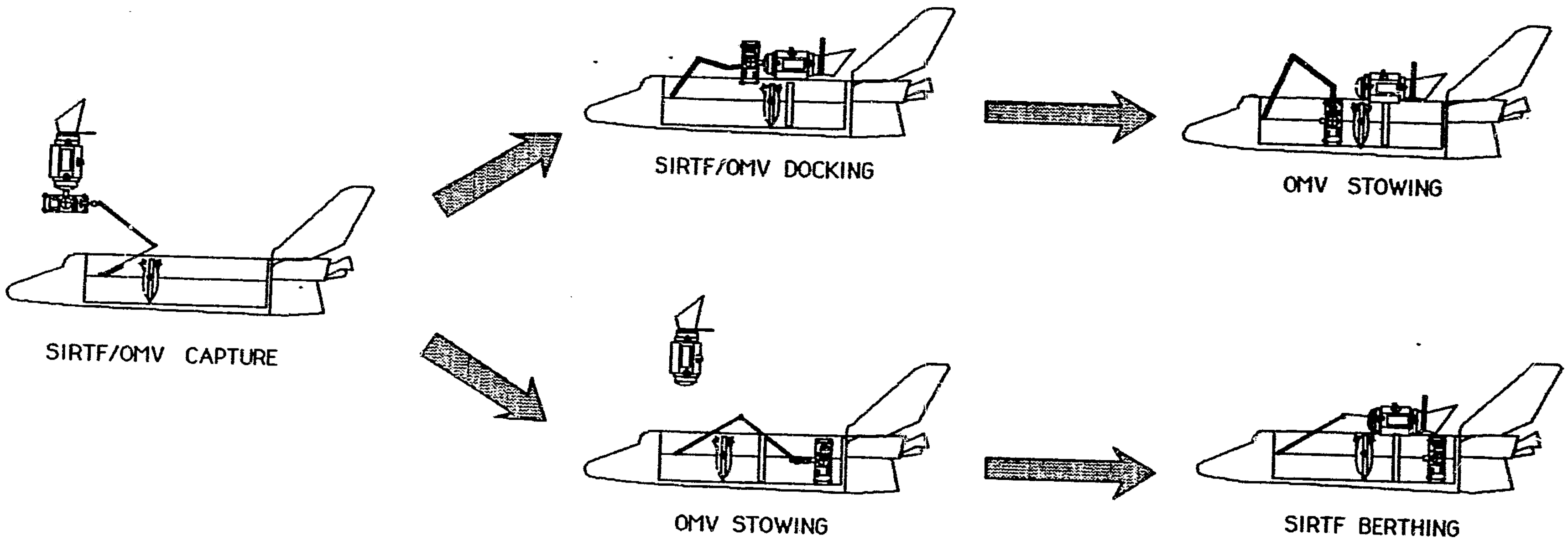

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Figure 4-5 SIRTF/OMV Capture Sequence Options

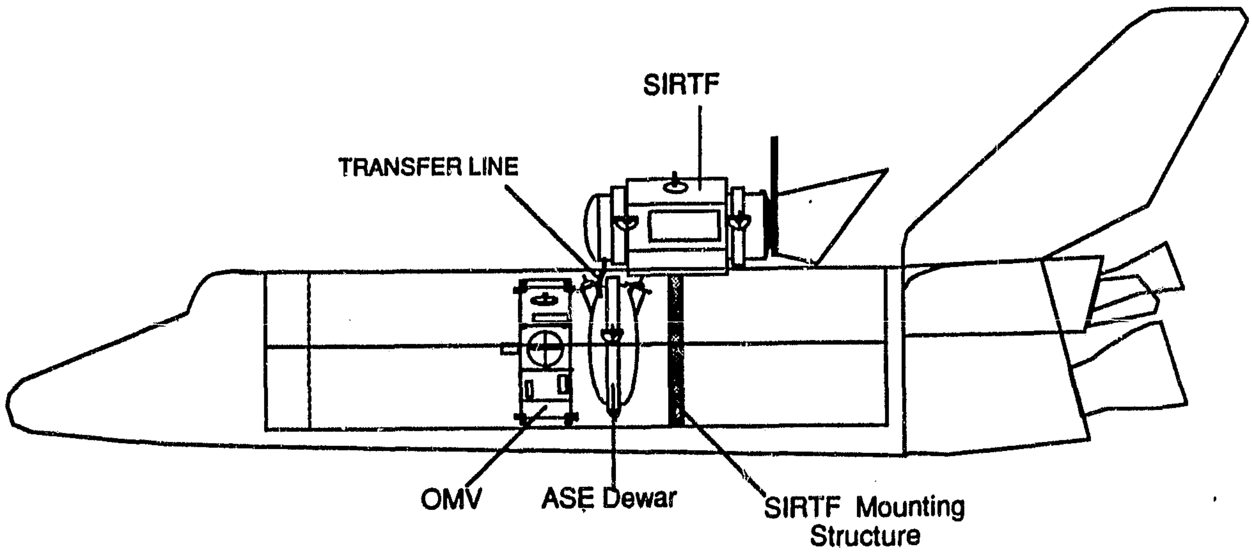

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Figure 4-6 Replenishment on Space Shuttle

back of the bay. One of the primary drivers for the location of the operation should be minimizing the contamination of the SIRTF due to firings of the Shuttle OMS and RCS. Although the SIRTF as shown has a belly band spacecraft, this position would also accommodate a leased platform spacecraft. A forward mounted position would be used if SIRTF were attached to the larger Space Platform.

The SIRTF mounting cradle is a modification of the MMS A cradle as discussed in Section 2.3 . Since there is no apparent need for rotational capability, the A Prime cradle is not required.

The positioning of the ASE dewar directly under the bottom end of SIRTF allows the use of a minimum length transfer line. Allowing for some degree of flexibility during attachment, the transfer line could be less than four feet in length. A simplified block diagram of the hardware connections are shown in Figure 4-7. Note that the SIRTF is electrically connected only to the ASE. The ASE dewar is connected to Shuttle power and data buses via the Standard Mixed Wiring Harness. The control console is located in the Aft Flight Deck and the Display and Manual Control Panel is a Shuttle Standard Switch Panel.

Operational Sequence and Timeline

A flow diagram of the operations for the replenishment activity on board Shuttle is shown in Figure 4-8. The name of the activity is written in the box representing the task. The initials of various resources required for that task appear in the upper right of, or below the box. The duration for the task in hours is above the upper right corner of the box. The durations are given for both times if there are alternate conditions for the operations such as starting with a 2K or 150K SIRTF dewar. In the case of Figure 4-8, numbers in parentheses refer to the times required for the task if SIRTF is at 150K when the replenishment operations are started.

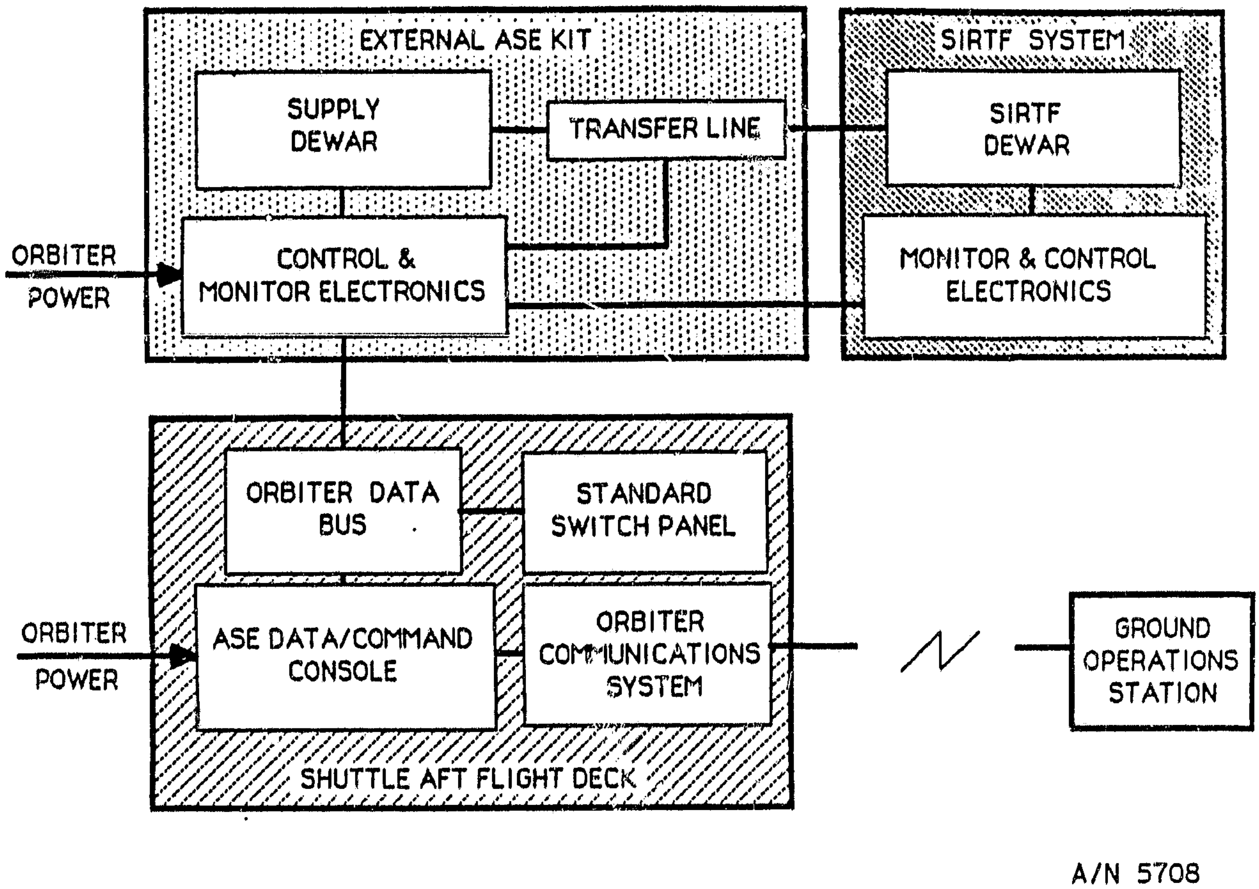

Figure 4-7 ASE Configuration on Orbiter

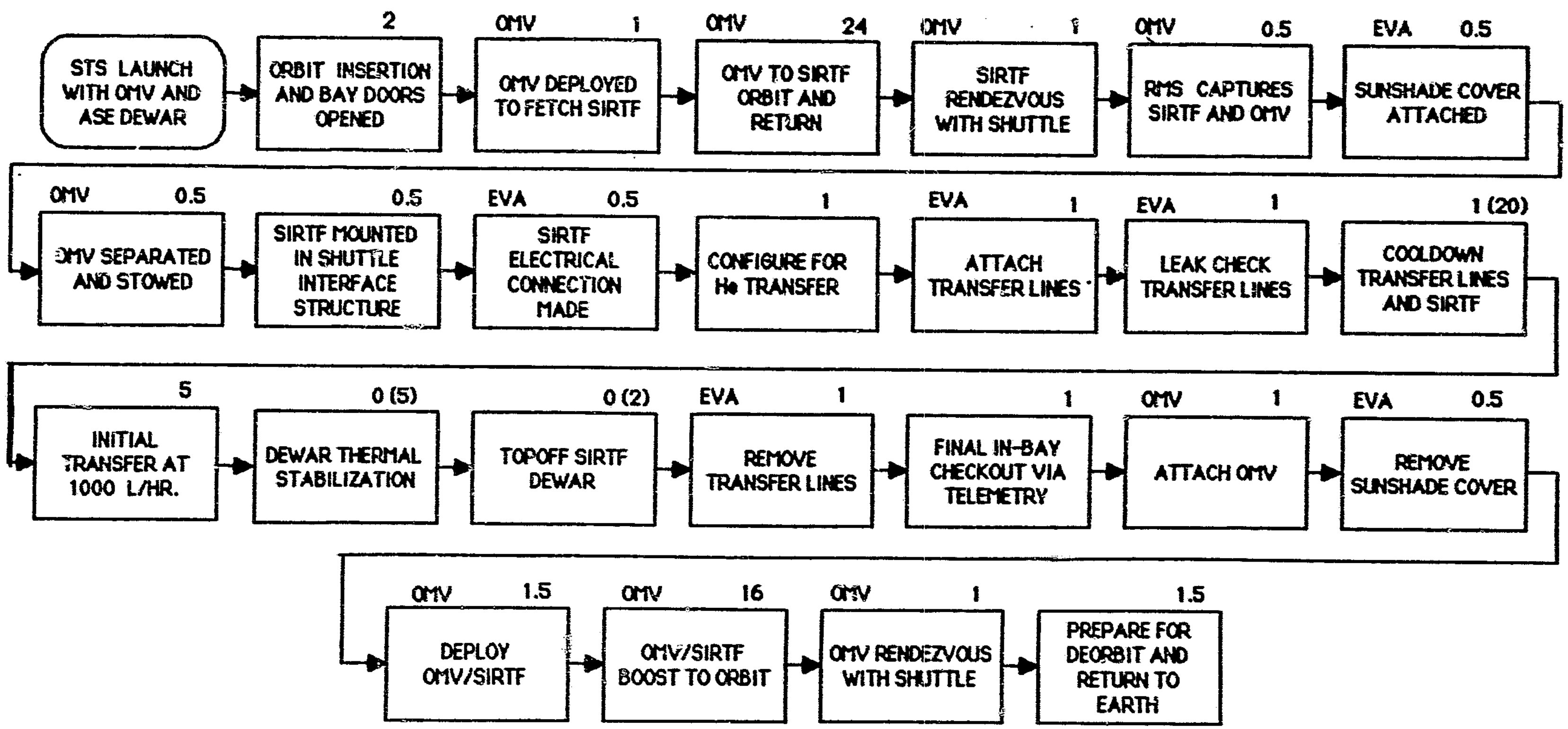

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Figure 4-8 Operations for Shuttle-Based Replenishment

The timelines for the operations appear in Figure 4-9 and Figure 4-10. The first timeline assumes that the SIRTF is still wet with helium at the start of the operation; the second assumes that SIRTF has been depleted of helium and reached a tank temperature of 150 K. In the first case, the cooldown time is one hour for cooling of the transfer lines only. There is no time required for instrument stabilization or topoff. The second case requires a 20 hour dewar cooldown plus stabilization and topoff.

Description of the Operations

- STS Launch- The Shuttle is launched into a 400 km orbit carrying the 5300 liter ASE supply dewar, an OMV, and the SIRTF support cradle in the bay. The ASE Control console computer is stowed in the Aft Deck Storage.

- Orbit Insertion- Two hours are allowed for orbit insertion and adjustment and the opening of the bay doors. It is assumed that a portion of the first day of the mission will be used for initial SIRTF activities.

- OMV deployed- One hour is allowed for the RMS to properly position the OMV for deployment.

- OMV to SIRTF rendezvous- The schedule for OMV to capture and return SIRTF to the Orbiter allows 24 hours. This is probably conservative since this maneuver could be performed in as little as 12 hours depending on the respective orbits of the Shuttle and SIRTF. However, the shorter OMV flight times will probably not shorten the overall schedule since the OMV would return during a crew rest period.

- Rendezvous with Orbiter- One hour is assumed to enable final orbital adjustments for rendezvous with the OMV.

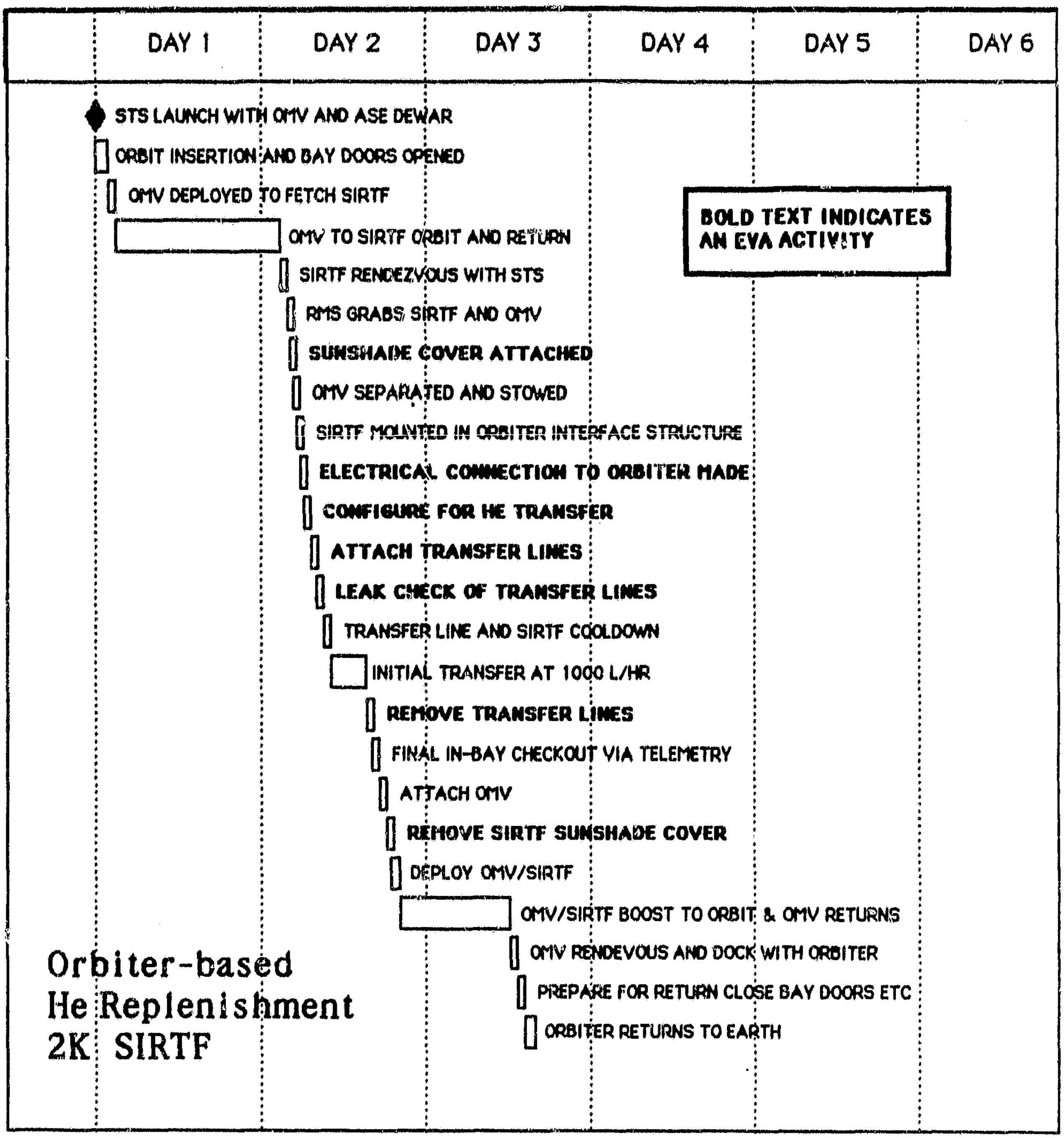

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Figure 4-9 Timeline for Shuttle-Based Replenishment of Cold SIRTF

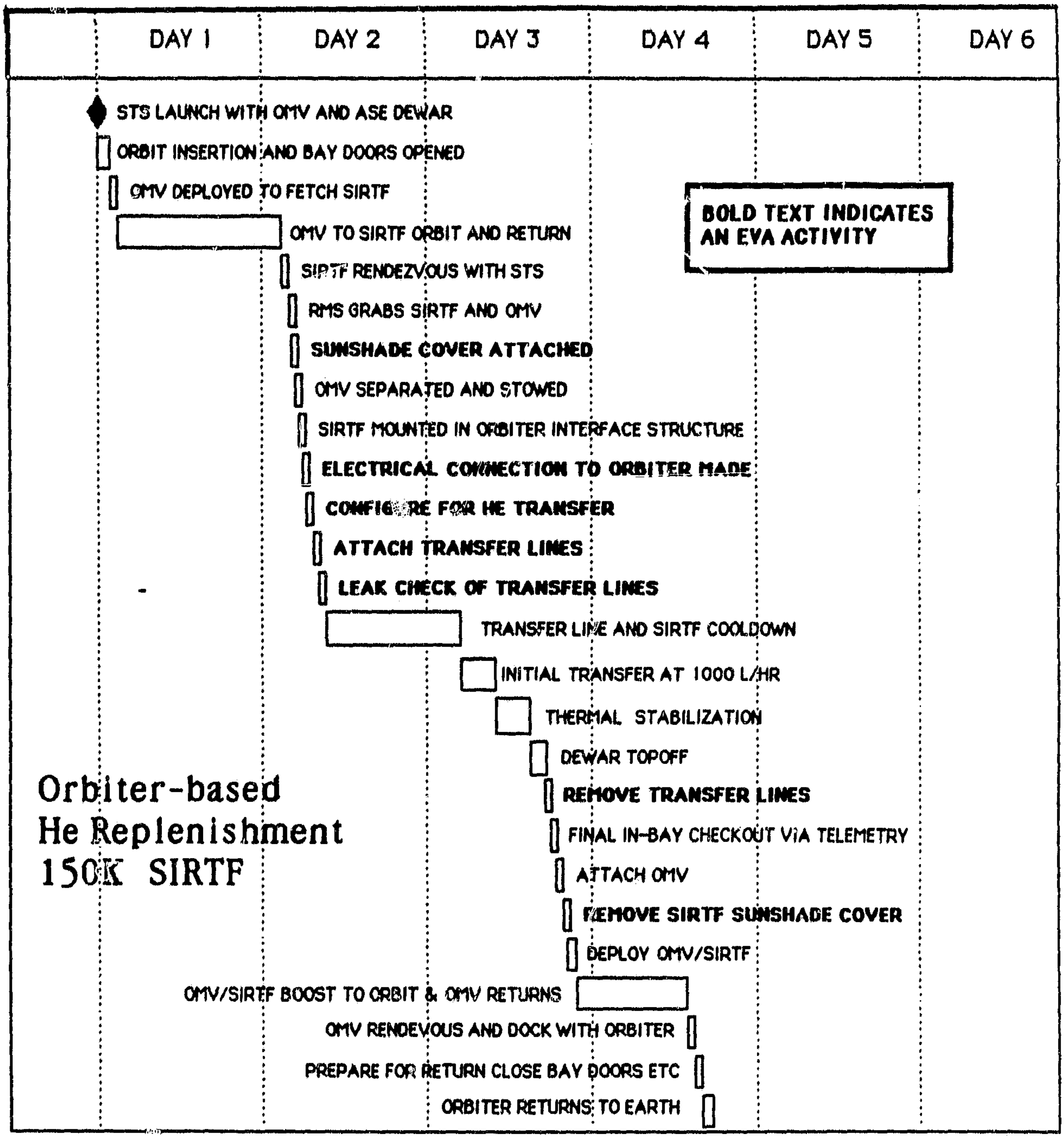

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Figure 4-10 Timeline for Shuttle-Based Replenishment of 150K SIRTF

c-3

- RMS capture- The RMS is used to capture the OMV/SIRTF and hold it in position.

- Sunshade cover attached- EVA is assumed for the task of covering the external aperture of the sunshade with a protective contamination cover. The Shuttle environment is not benign with regards to particle contamination, and the scatter sensitive inner cone of the sunshade must be protected as soon as possible. It would also be possible to use the RMS to install a suitably designed cover. This would eliminate the need for this EVA.

- OMV stowed- The OMV is placed in its storage position and battery recharge cable is connected.

- SIRTF mounted in mounting structure- The service structure is used to hold the SIRTF out of the bay. This is necessary if the SIRTF is mounted to a large spacecraft such as leased platform but in any case would probably be used to minimize the amount of bay space taken up by the operation. The total period from the capture of the OMV/SIRTF until both are secured should be less than two hours.

- Electrical connections- The umbilical from the ASE dewar to the SIRTF is made at this time. EVA is assumed. A remote connection could be set up such that electrical connection occurred when the SIRTF was set in its mounting structure.

- Configure for transfer- Preliminary electrical check of the SIRTF system umbilical, valve status, thermometry and general status of the transfer system.

- Attach transfer lines- EVA is assumed for the connection of the transfer lines. The line is removed from its storage position on

the ASE dewar, interfaces are inspected, and the line is installed. This is the most difficult operation to perform remotely.

- Leak check of interconnects- The transfer line bayonets are checked for leaks by an external helium source or by the supply dewar boiloff. A hand held or RMS held mass spectrometer could be used for this operation. After this operation the EVA crew would return to the cabin or perform other duties in the bay not associated with SIRTF. The EVA would probably continue until the leak check was complete to allow inspection or treatment of a suspect leak without the delay associated with resuiting in the EMU's.

- Cooldown- At this point the transfer process would start and the cooldown of the transfer lines would be performed. If the SIRTF was depleted of helium to start with, then the cooldown would continue for 20 hours until liquid started to collect in the receiver dewar.

- Transfer of helium- The transfer should take less than 5 hours at The anticipated 1000 liter/hour rate with the thermomechanical pump.

- Thermal Stabilization- In the event that the dewar was initially dry, it would be necessary to allow the instruments to continue to cool down until the dewar boiloff stabilized. This time depends strongly on the instruments internal thermal design, and could range from 5 to 24 hours, depending on initial temperatures. This time would be used for various health checks of SIRTF including instruments checks if the system is configured to allow them.

- Topoff- Again, in the case of starting with a dry dewar, the final cooldown of the instruments would consume a small portion of the helium transferred initially. This would be replenished by a topoff operation.

- Final in-bay checkout- A checkout of the transfer operation is performed, valve positions, temperatures, and boil off rates are monitored.

- Remove transfer lines- EVA is used to remove the transfer lines and secure them to the ASE dewar.

- Attach OMV- The RMS lifts the OMV from its berth and attaches it to SIRTF. Depending on the stow position of the OMV, this may occur after SIRTF has been undocked and positioned away from the Shuttle.

- Remove sunshade contamination cover- EVA is assumed as the baseline but remote operation is possible.

- Deploy OMV/SIRTF- The pair are deployed by the RMS.

- Final checkout via telemetry- A final health check of the SIRTF system can now be performed via telemetry. This is the final opportunity to elect to abort the orbit transfer operation and bring SIRTF back to earth. In the event of an abort, the OMV would be separated and stowed, and the abort procedures discussed in 4.2 would be initiated.

- Orbit transfer and insertion- This operation has been allowed 16 hours. Since there is no time required for rendezvous at the higher orbit, it will be a shorter mission than the one to fetch SIRTF. OMV deorbits to 400 km.

- OMV rendezvous with Orbiter- OMV is captured by the RMS and secured for reentry.

- Prepare for reentry- Final general preparations for reentry. The 1.5 hours allowed here are arbitrary and could be whatever is necessary.

- Orbiter returns

Discussion of the Timelines

As mentioned earlier, we are carrying two options for the transfer operation that influence the mission timeline. The first is that the SIRTF will be serviced before its previous helium supply has been exhausted. The end-to-end timeline for this appears in Figure 4-9. The second timeline assumes that the SIRTF will be dry and at 150K tank temperature at the time of the replenishment operation. This is shown in Figure 4-10. There are several observations to be made by examining these timelines.

Timeline for "2K" SIRTF

- The shaded blocks indicate that EVA is required for the operation. The beginning of the second day would require that the EVA crew start the four hour long task of donning their suits while the Orbiter and OMV perform rendezvous and docking operations.

- The first EVA will last approximately 5 hours and includes installation of the sunshade cover, attachment of electrical umbilical and transfer lines, and support for the leak check operation. This EVA could be shortened by one to one and one-half hours, but not eliminated, if the installation of the cover is performed by the RMS.

- The transfer operation is started in the middle of the second day of the flight and continues into the beginning of the crew rest period. At this point there will be slack time in the operation sequence since the next activity, the disconnection of the transfer line, cannot begin until after completion of the crew rest period and the four hour effort of donning their EMU's. This period could be used by the POCC to perform additional health checks on the SIRTF (this is an argument for providing full instrument telemetry as well as dewar telemetry).

- The second EVA will last about four hours and consist of disconnecting the transfer lines and umbilicals and removing the sunshade cover prior to separation of the OMV and SIRTF. The cover should be left on for as long as possible in the interest of minimizing particle contamination if the sunshade. Again, if this procedure were to be performed remotely, it would reduce the length of the EVA period but not eliminate it.

- The total elapsed time is 77.5 hours including 13.5 hours of slack time in day 2 of the mission.

Timeline for "150K" SIRTF

- Up to the point of the cooldown operation, both timelines are identical. The cooldown of the 150K tank takes 20 hours and carries this operation into the 3rd day of the mission. Since there is no need to wait for the end of a crew rest period to continue operations, there will be no slack time available after the fill operation for system health checks. However, the time period required for thermal stabilization prior to topoff should allow ample opportunity for any SIRTF testing deemed necessary.

- The second EVA required to disconnect the transfer lines would start late into the third day of the mission. This time would

normally be a crew rest period and hence the EVA might be postponed until the fourth day of the mission. This would extend the mission an additional 12 hours or so.

- This operation takes a total of 92 hours as shown.

Shuttle Interfaces

- The ASE dewar uses the 3-point longeron mounting scheme in the Shuttle bay. No cradle is required since the longeron and keel fittings are part of the dewar structure as shown in Figure 4-11 and 4-12. The 5300 liter dewar used for the replenishment mission occupies approximately 70 inches of bay length. Two feet on either side of the dewar are required for working room or RMS access if required. Two RMS grapple fixtures are provided on the dewar to allow transfer to Space Station.

- The dewar vent valves would be controlled by redundant barometric controllers for opening during ascent or closing in the event of an abort and descent. An electrical connection to the dewar via a SURS connector would allow emergency manual valve actuation from a Standard Switch Panel.

- The dewar would be allowed to vent into the Shuttle bay during most operations. This is the current procedure for the the COBE dewar. There is a possibility that a detailed safety analysis of the emergency venting rates in the event of a catastrophic leak in the dewar guard vacuum would necessitate overboard venting of the helium.

- The peak power requirements of the ASE and SIRTF during the transfer operations would be 200 watts. This is assumes multiple, simultaneous valve actuation, which is rarely the case. Normally, the system would require less than 100 watts for

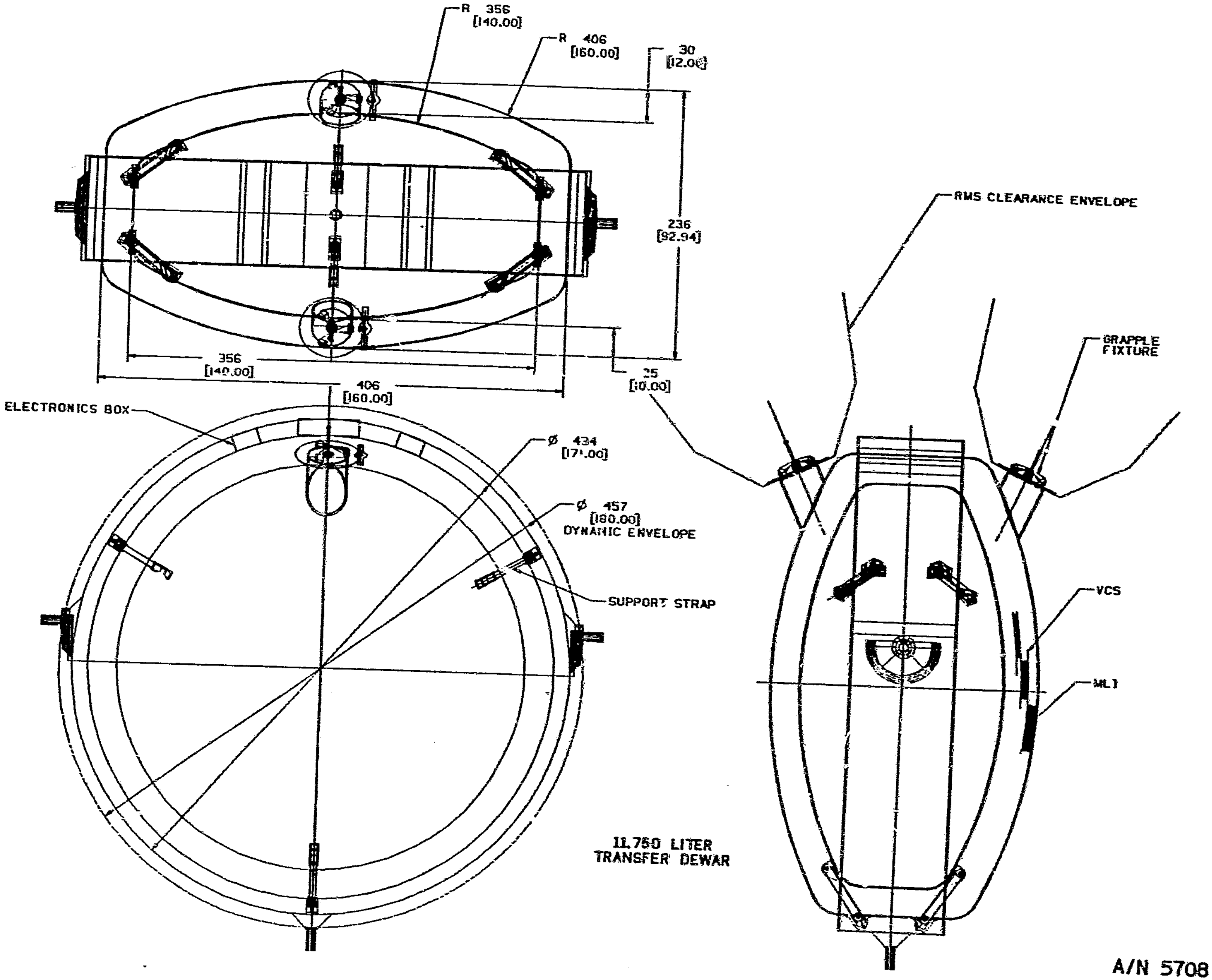

Figure 4-11 11750 Liter Transfer Dewar

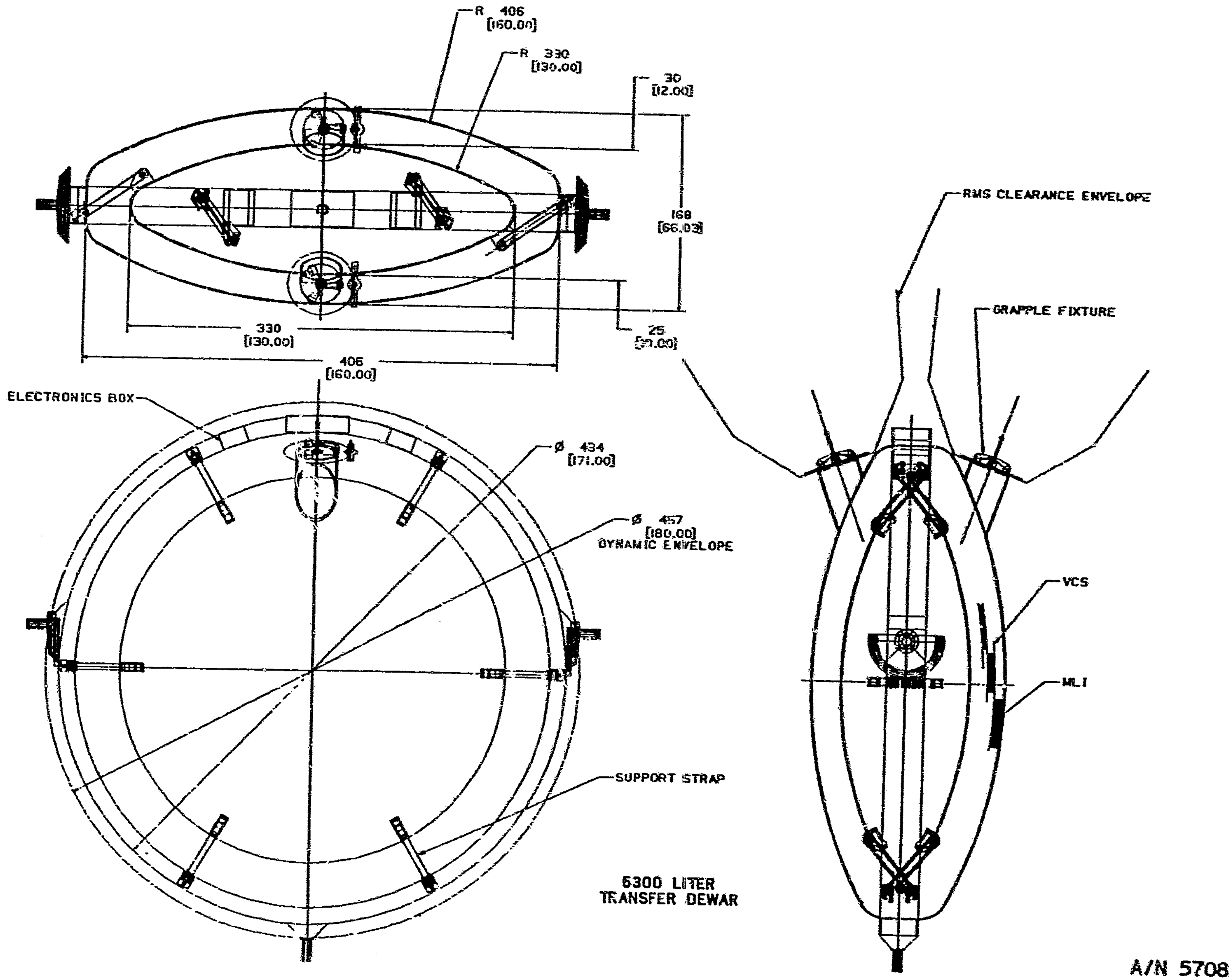

Figure 4-12 5300 Liter ASE Dewar

transfer and monitoring operations. Power and data interconnects are provided by Shuttle via the Standard Mixed Wiring Harness in the cargo bay.

- The modified A frame also uses a three point retention scheme for the longeron and keel attach points. It would also provide electrical connection to the SIRTF if a telemetry link to SIRTF through the Shuttle were required. Otherwise the SIRTF umbilical connection to the ASE will provide power and commands for the transfer operation. The mechanical interface of the A frame to SIRTF is described in section 2.

- The replenishment mission requires a total of two EVAs. The duration of the first is six hours; the second is four hours. An additional crewmember is assumed for data monitoring and RMS manipulation.

4.3.3 Space Station-based Replenishment Operations

For Space Station based operations we have assumed the IOC Reference Configuration per JSC-19989, the "power tower" configuration, for the station capability baseline. This was for convenience in communication; the mission description and timelines are not sensitive to the final configuration except for the following assumptions:

- Shuttle-style rail and keel mounting structures will be available

- An enclosed bay, providing contamination protection, will be available

- The Mobile Remote Manipulator System (MRMS) or equivalent will be available.

- The OMV will be available from Station.

- Power and data buses will be available both on the structure and in the inhabited module.

- Two month or longer storage of the ASE dewar with continuous automated monitoring will be possible.

Mission Scenario

The top level scenario for the Station-based replenishment operation is shown in Figure 4-13. Here, the ASE is transported to the Space Station during one of the routine service missions that are scheduled to occur on two month intervals.

After docking at Station, The Station Mobile Remote Manipulator (MRMS) removes the ASE dewar from the Shuttle bay and carries it to an interim storage area. This storage area will probably be the "tank farm" located on the lower keel, above the inhabited modules. The ASE dewar will be stored here for up to two months awaiting the arrival of SIRTF.

Sometime during this two month period, an OMV will be dispatched from Station to fetch SIRTF. The OMV/SIRTF will rendezvous with Station and the SIRTF will be brought to a service hanger on the lower keel for the transfer operation.

After the transfer operation is complete, the SIRTF will be returned to 900 km orbit by an OMV, and the ASE dewar will be returned to storage to await the next available Shuttle slot for the return trip to Earth. There is nothing critical about the overall schedule, except that manifesting of the ASE on a supply mission occur within a two month window of the retrieval of SIRTF.

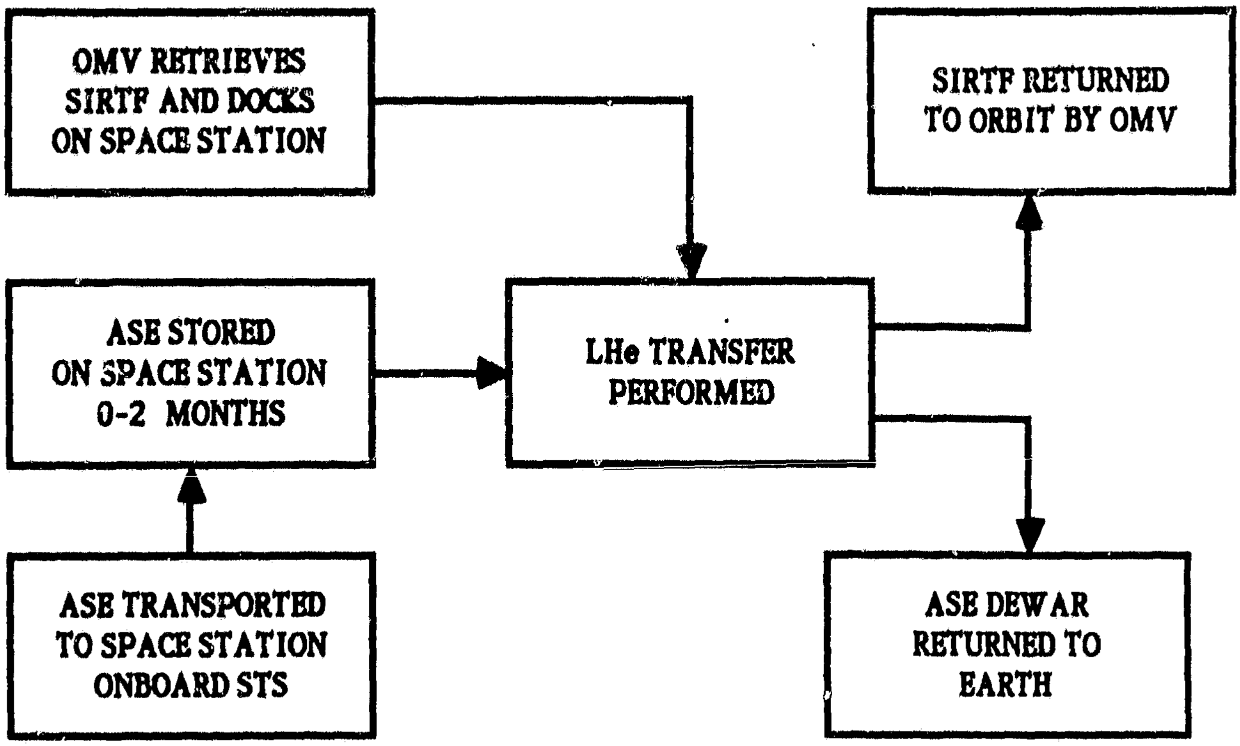

Figure 4-13 Space Station-Based Replenishment Scenario

Hardware Configuration

The probable locations of the storage site for the ASE dewar and the transfer operation on Space Station are shown in Figure 4-14. After the ASE dewar is transported to the Space Station by the Shuttle on a routine supply mission, the Station MRMS will remove it from the Orbiter bay. Alternately, the ASE dewar is provided with two opposing grapple fixtures that permit the RMS to pick the dewar out of the bay and hand it off to the Station MRMS. The MRMS the moves along the station structure to the lower keel.

There the dewar is mounted on Shuttle- style longeron mounts that are attached to the keel structure. The ASE dewar is designed with its own external thermal control finishes and does not have to be stored in any sort of thermal enclosure.

The dewar electronics are attached to the Space Station data and power bus to allow monitoring of the dewar health during the storage periods. We have assumed that an automatic monitoring procedure would be used for the the dewar that would sound an alarm if an over-limit condition occurrs, but would not otherwise require attention by the crew.

Prior to the arrival of SIRTF, the MRMS would move the ASE dewar into the Refuel Bay, also located on the lower keel. After being separated from the OMV, SIRTF would be also brought into the Refueling Bay, where the transfer operation would take place. The suggested configuration of the ASE and SIRTF during the transfer operation is shown in Figure 4-15. The SIRTF and the ASE dewar are both mounted on longeron mounts as they would be in the Shuttle bay. The configuration allows a transfer line that is less than five feet in length.

As described in section 2.3.5 and 4.4.2, the electrical power and command lines to SIRTF are over hard line from the external ASE electronics, which in this case are hooked to the Space Station power bus and data bus as shown in the simplified block diagram in Figure 4-16. The ASE Command

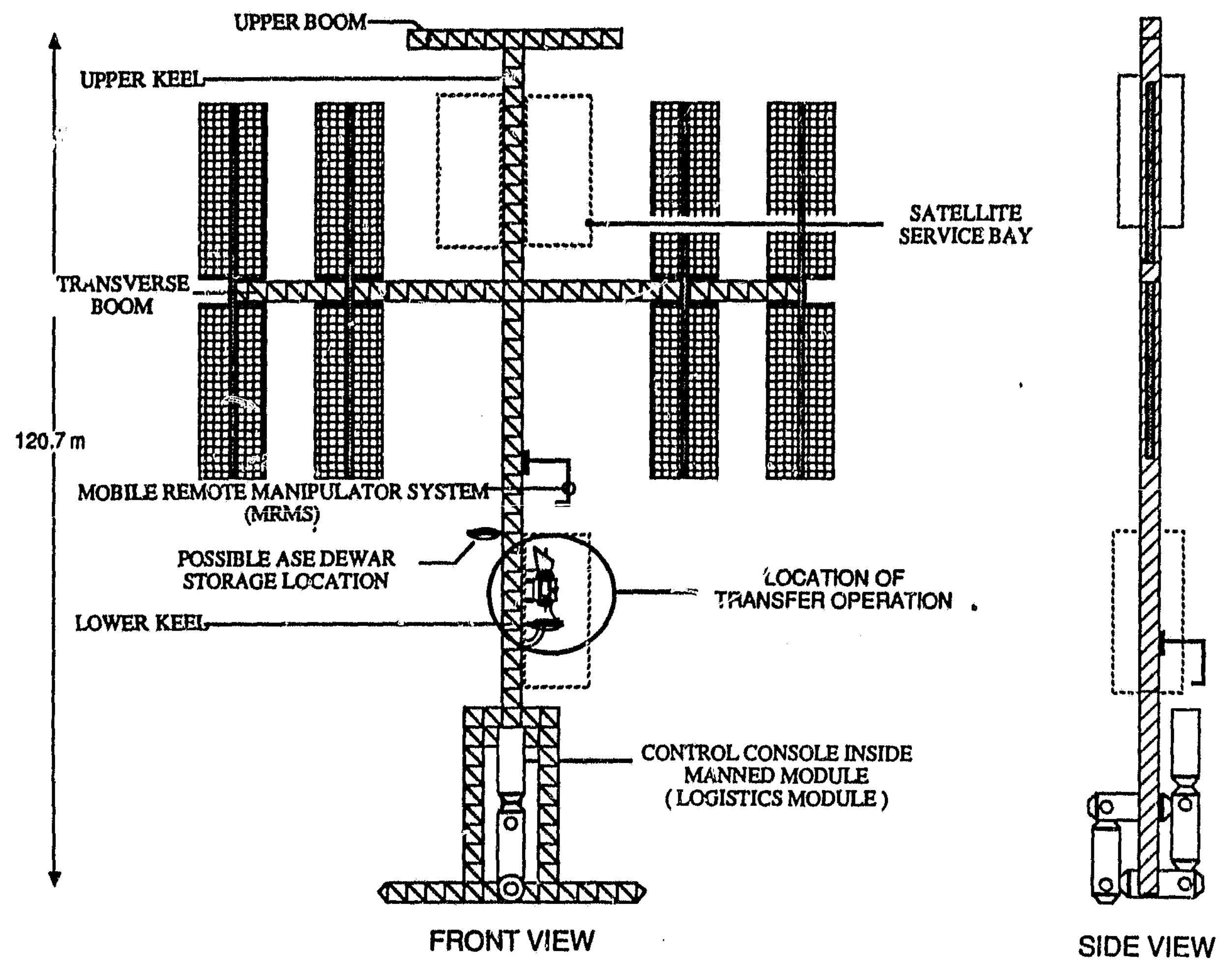

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Figure 4-14 Storage and Transfer on Space Station

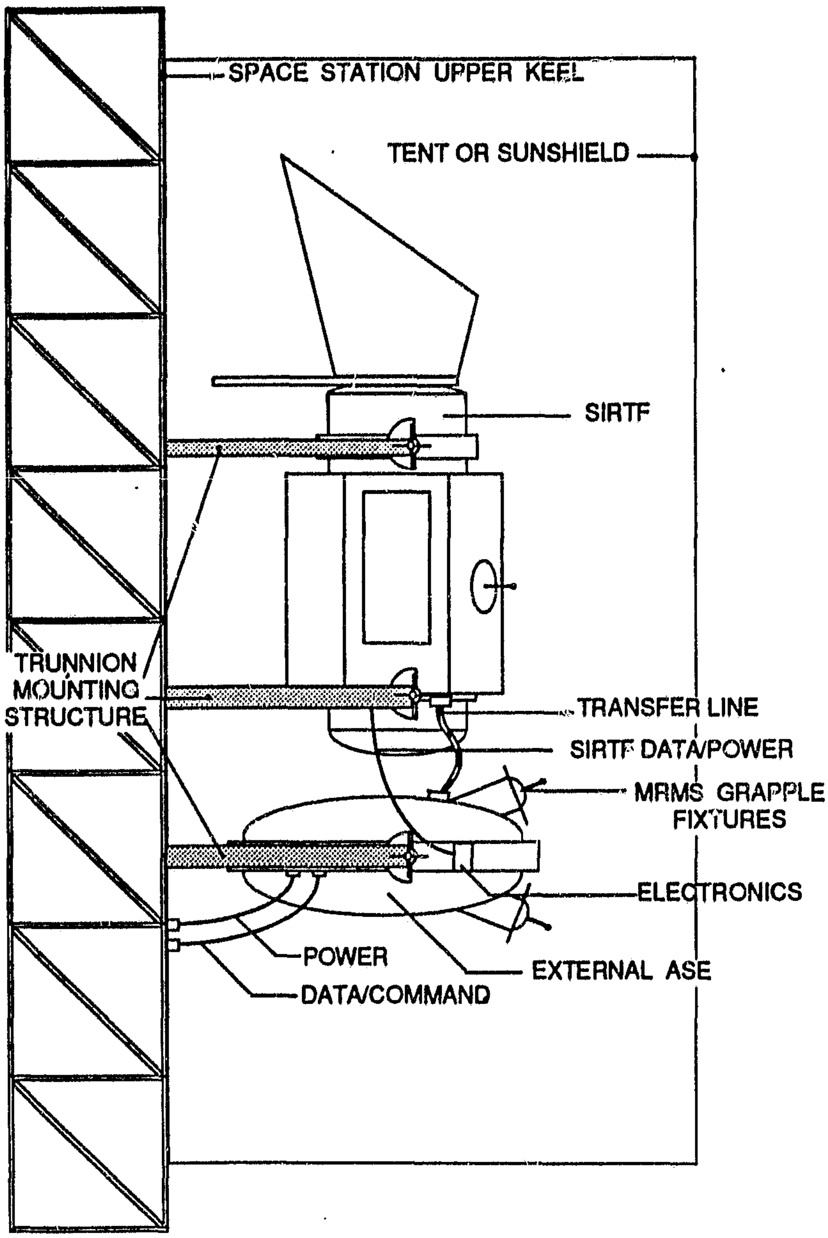

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Figure 4-15 Configuration for Replenishment on Space Station

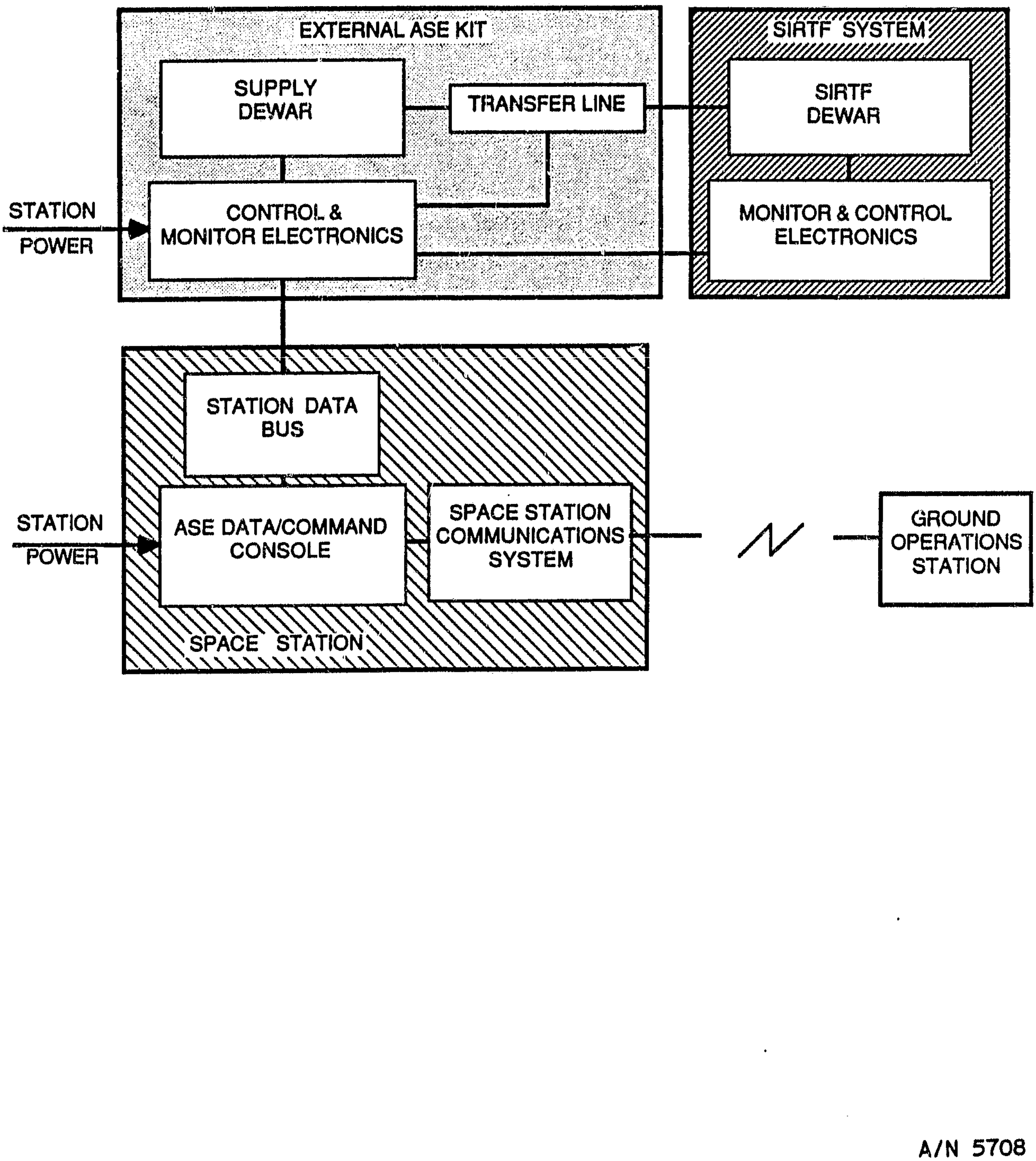

Figure 4-16 ASE System Configuration on Space Station

Console and Internal Electronics are located inside the Logistics Module, and communicate with the external electronics via the Station data bus.

Operational Sequence and Timeline

A flow diagram of the operations for the replenishment activity onboard Space Station is shown in Figure 4-17. The description of how the flow diagram is laid out appears in section 4.4.2. As before, numbers in parentheses refer to the times required for the task if SIRTF starts the replenishment operations dry.

The timelines for the operations appear in Figure 4-18 and Figure 4-19. Again, the first timeline assumes that the SIRTF is still wet with helium at the start of the operation, the second assumes that SIRTF has been depleted of helium and achieved a tank temperature of 150 K. In the first case, the cooldown time is 1 hour and only applies to the transfer lines. There is no time required for instrument stabilization or topoff. The second case requires a 20 hour dewar cooldown plus stabilization and topoff.

Description of the Operations

- OMV to retrieve SIRTF- the schedule for OMV to capture and return SIRTF to the Orbiter allows 24 hours.

- Relocation of ASE dewar- The ASE dewar is moved from its storage area to the refueling bay and connected to the Station power bus and Data bus.

- SIRTF docking- The MRMS is used to capture the OMV/SIRTF , the two are separated and SIRTF placed in the refuel bay. The OMV is moved another refueling area for refueling and battery recharge.

- Sunshade cover attached- EVA is assumed for the task of covering the external aperture of the sunshade with a protective contami-

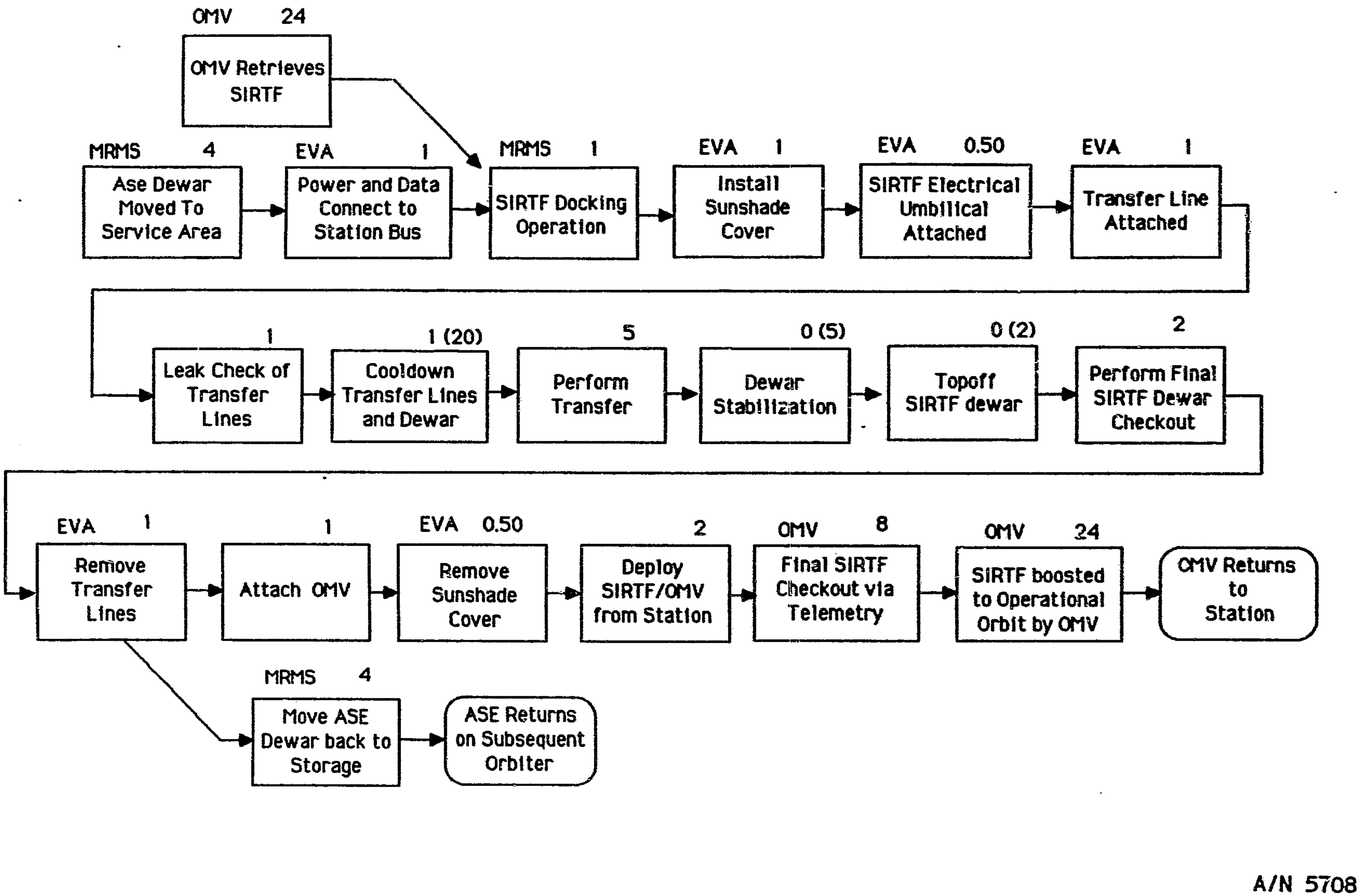

Figure 4-17 Operations for Station-Based Replenishment of SIRTF

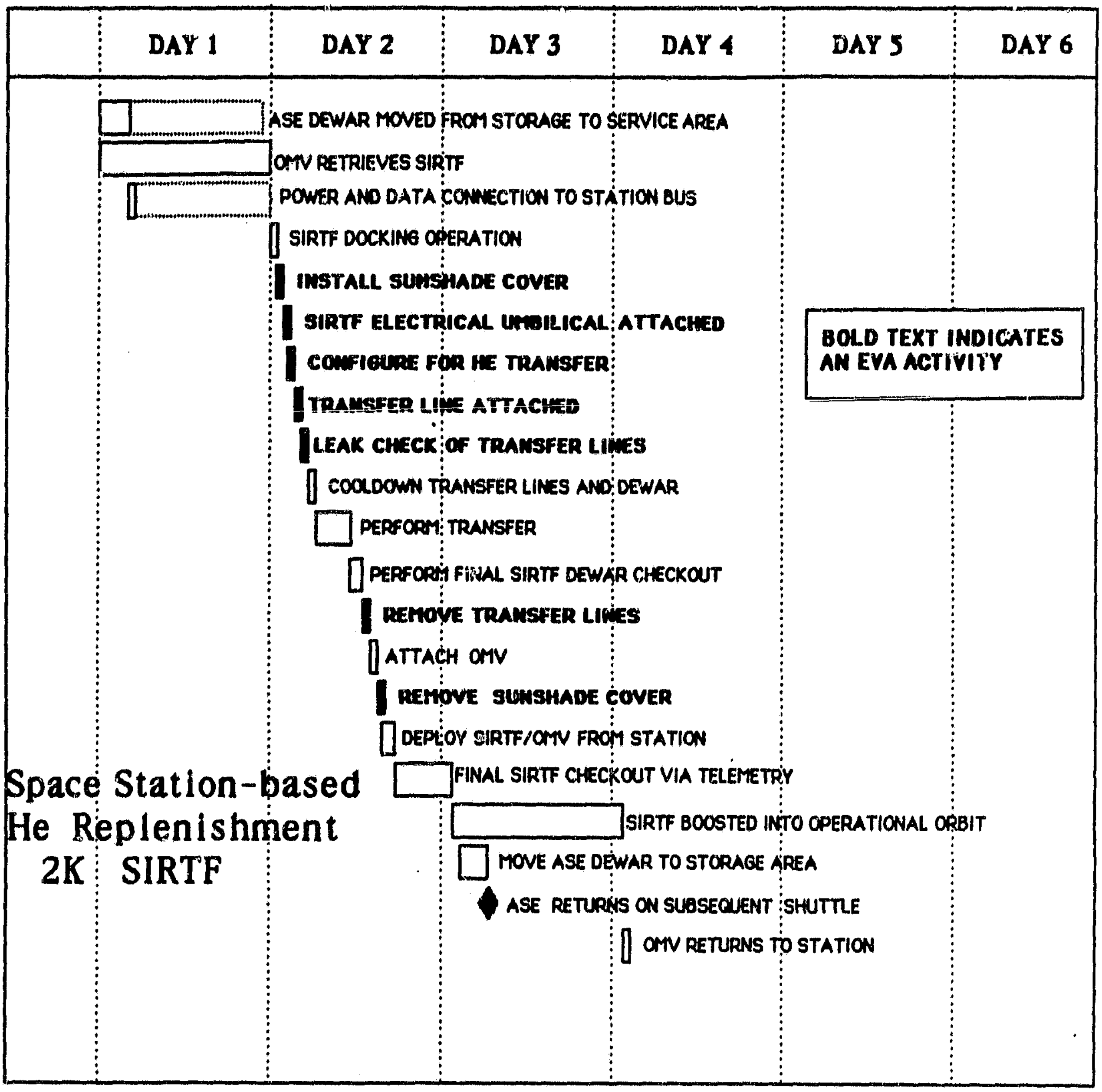

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Figure 4-18 Timeline for Station-Based Replenishment of Cold SIRTF

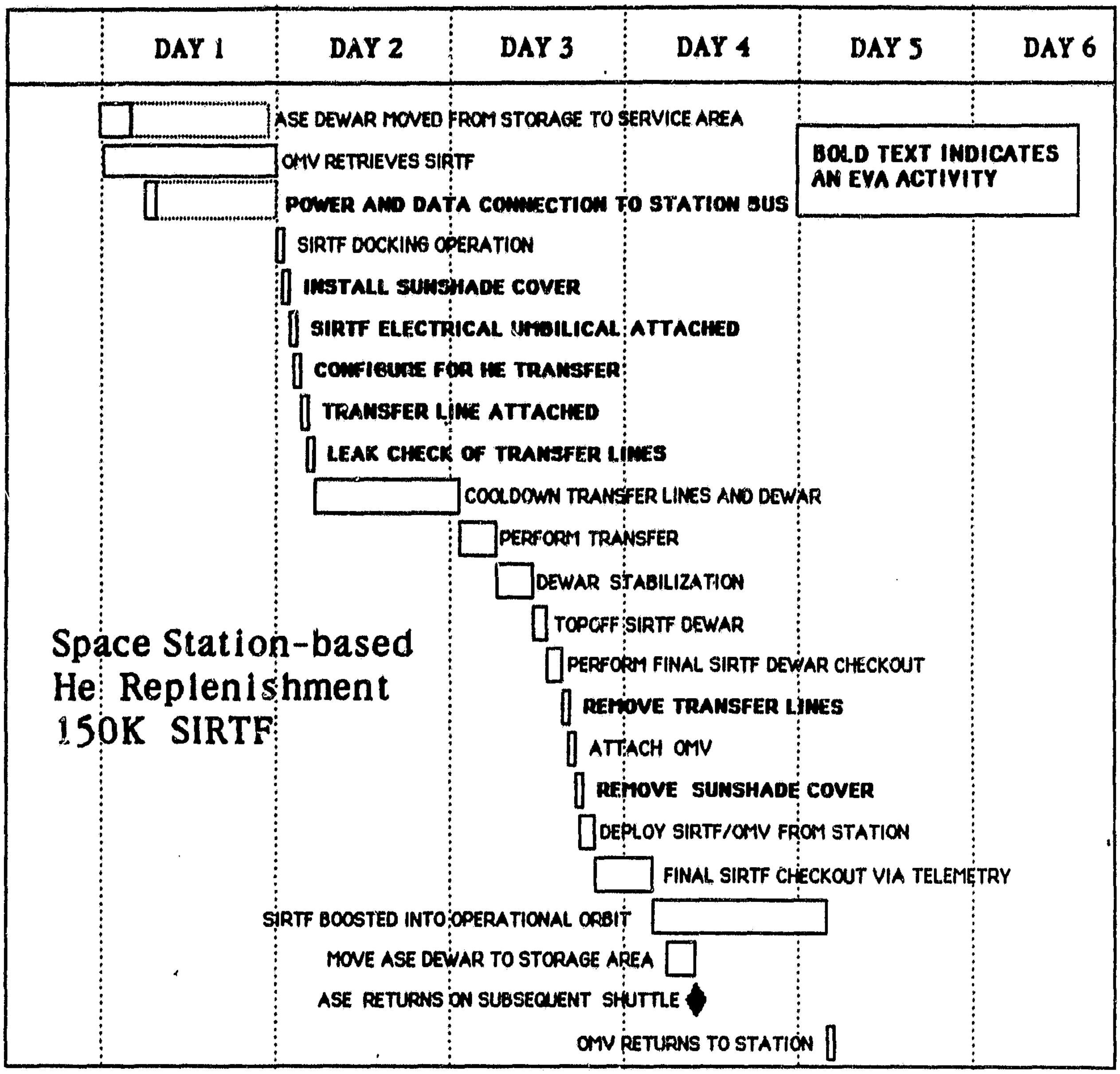

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Figure 4-19 Timeline for Station-Based Replenishment of Warm SIRTF

nation cover. It would also be possible to use the MRMS to install a suitably designed cover. This would eliminate the need for this EVA.

- Electrical connections- The umbilical from the ASE dewar to the SIRTF is made at this time. EVA is assumed. A remote connection could be set up such that connection occurred when the SIRTF was set in its cradle.

- Configure for transfer- Preliminary electrical check of the SIRTF system umbilical, valve status, thermometry and general status of the transfer system.

- Attach transfer lines- EVA is assumed for the connection of the transfer lines. The line is removed from its storage position on the ASE dewar, interfaces are inspected, and the line is installed. This is the most difficult operation to perform remotely.

- Leak check of interconnects- The transfer line bayonets are checked for leaks by an external helium source or by the supply dewar boiloff. A hand held or RMS held mass spectrometer could be used for this operation. As with the Shuttle operation, this EVA would probably continue until the leak check was complete to allow inspection or treatment of a suspect leak without the delay associated with resuiting in the EMU's.

- The following operations occur in the same manner as explained for the Shuttle based transfer in section 4.4.2:
  - Cooldown
  - Transfer of He
  - Thermal Stabilization
  - Topoff

The only difference is that there is no concern about phasing operations with crew rest periods on the Station, so there is no forced slack time as there was with the Orbiter-based transfer.

- Final checkout- A checkout of the transfer operation is performed, valve positions, temperatures, and boil off rates are monitored.

- Remove transfer lines- EVA is used to remove the transfer lines and secure them to the ASE dewar.

- Attach OMV- The MRMS moves the OMV from its berth and attaches it to SIRTF.

- Remove sunshade contamination cover- EVA baseline but remote is possible.

- Deploy OMV/SIRTF- the pair are released by the MRMS.

- Final checkout via telemetry- A final health check of the SIRTF system can now be performed via telemetry. This is the final opportunity to elect to abort the orbit transfer operation and maintain the SIRTF on Station or bring it back to earth. In the event of an abort, the OMV would be separated and stowed, and the abort procedures discussed in 4.2 would be initiated.

- Orbit transfer and insertion- This operation has been allowed 24 hours.

- OMV returns to Station- OMV is captured by the MRMS and returned to its storage bay.

- ASE moved back to storage area- The ASE is returned to storage until the next available Shuttle back to earth.

Discussion of the Timelines

As discussed in Section 4.4.2, we are carrying two options for the transfer operation that influence the mission timeline, a "2K" and a "150K" SIRTF. The end-to-end timeline for the "2K" SIRTF appears in Figure 4-18. 150K SIRTF is shown in Figure 4-19. The timelines for the Station-based operations are not as critical as those for the Orbiter-based transfer since there is no pressure from a time limited mission to optimize the schedule. The main comment to make therefore is that these timelines represent the minimum amount of time necessary to perform the transfer. However, there is no reason why the operations cannot be conducted in a more leisurely fashion. Again, the shaded blocks indicate that EVA is required for the operation.

- The minimum time for the the transfer to a wet SIRTF is 74.5 hours including the retrieval and return to orbit by the OMV.

- The minimum time for the transfer to a wet SIRTF is 98 hours under the same condition.

Space Station Interfaces

This is a summary of the interfaces to Space Station:

- The ASE dewar uses the 3-point longeron mounting scheme in the Orbiter bay. Presumably, station will be able to provide a mechanical interface equivalent to the sill and keel fittings of the Orbiter bay. Two RMS grapple fixtures are provided on the dewar to allow transfer to Space Station MRMS by the Orbiter RMS if required.

- The ASE dewar interfaces to the station data bus via the Station-provided interface system. There will be data bus interface ports available on the keel, in the logistics and other modules

and presumably in the satellite service bay or the refueling bay. The data bus may be hardwire, fiber optic or RF based, but in any case will require a standard interface box on both the dewar and control console sides as shown in Figure 4-20.

- The SIRTF dewar would be mounted to the Station on Shuttle longeron fittings using either the three or five point mounting scheme. The transfer operations would be performed in the refueling bay. This bay must provide contamination protection from the general station outgassing and particulate environments.

- The ASE dewar external thermal finish α/ϵ will be 0.20-0.30. In order to maintain main shell temperatures below 310K inside the refueling bay, the total power dissipation in the service area enclosed by the bay must be below 0.5 kW. The ASE dewar can be stored on the station keel outside of a bay or tent until the time of the actual transfer operation.

- The peak power requirements of the ASE and SIRTF during the transfer operations would be 200 watts. This assumes multiple, simultaneous valve actuation, which is rarely the case. Normally, the system would require less than 100 watts for transfer and monitoring operations. Power would be provided by the Station power bus.

- The replenishment mission requires a total of two EVA's. The duration of the first is six hours; the second is four hours. An additional crewmember is assumed for data monitoring and RMS manipulation.

4.3.4 Platform-based Replenishment

As discussed in Section 4.2, a platform-based SIRTF could be serviced by Space Station, the STS Orbiter or remotely by a teleoperated OMV. OMV-based

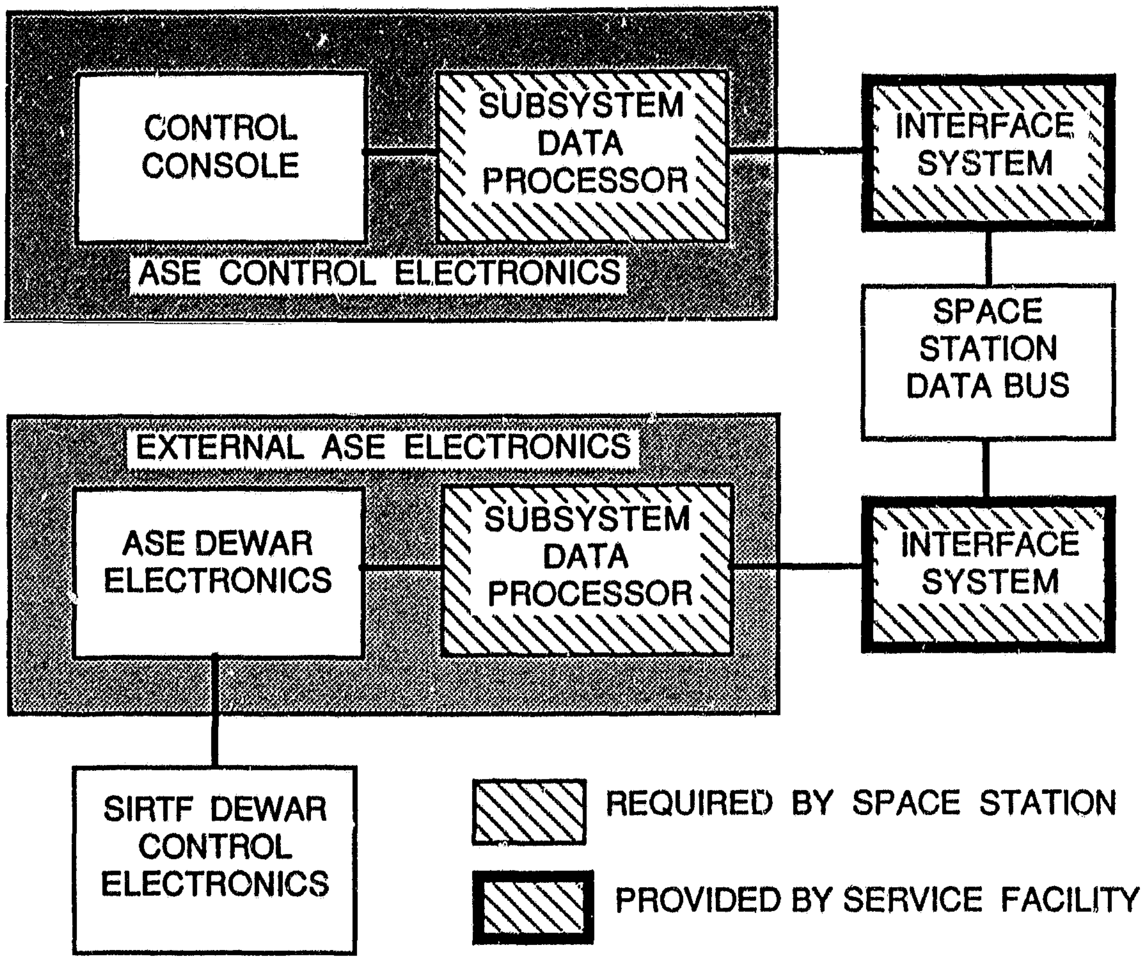

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Figure 4-20 Data/Command Interface to Station Data Bus

servicing obviously would require the development of robotic techniques for all operations, and is not addressed in this study. A service mission on Space Station or the Orbiter would essentially have the same operations scenario and timelines for the platform as we have shown for our baseline free flying satellite. Rather than repeat those discussions in detail, we will focus on some of the major advantages and disadvantages of servicing SIRTF on platform as compared to a dedicated satellite.

The single major advantage that servicing on platform will offer is that the operations and techniques for performing general servicing on co-orbiting platforms will be well established for both Space Station and Shuttle-based operations. This does not say anything about the SIRTF specific operations but it does mean that retrieval of platforms, docking and undocking, OMV interfaces, etc., will have been developed and flight-tested on other, earlier platforms before it will be necessary to perform the first replenishment operation for SIRTF. Although this advantage is partially offset by the fact that this experience and experience with other types of spacecraft is in some part transferable to any spacecraft that SIRTF may fly on, the knowledge and background associated with servicing of platform-based instruments will exceed that of any unique spacecraft.

The primary disadvantage stems from the overall size and mass of the platform itself, compared to a free flying satellite. The size will make the docking operation with the Orbiter a more clumsy operation and requires additional interface structures to support the platform other than the simple configuration of the SIRTF supported by a modified A frame that we have shown. Supporting the massive platform solely through the SIRTF mounting would place unnecessary stress on the gimbaling system.

Another disadvantage of the platform stems from the fact that it will probably have its own propulsion system. The propulsion system is proposed to include 6500 pounds of propellant and 1200 pounds of structure. It would initially be used to boost the platform to its operational altitude of 900 km, and then be used to deorbit the platform for Station or Shuttle based

cryogen replenishment. This same propulsion system would most likely be used to return the platform back to operational orbit after the servicing is complete. This requires that the propulsion system be replenished during the same timeline as the cryogen replenishment operations. For the Station based operations, this does not present a major schedule problem. It may not have an significant impact on the Shuttle-based replenishment either, but as will be discussed in the next section, there is very little margin available for any additional operations in the timeline shown for instrument changeout. Any additional time required to perform a refueling operation, particularly if EVAs are required, will extend the changeout mission beyond the seven day limit. A concurrent refueling operation of the platform could also have some contamination implications, but presumably one of the goals of the refueling technique development will be to eliminate the possibility of contamination. If the platform does not have its own propulsion system but uses the OMV instead, then the refueling will not be required.

4.4 INSTRUMENT CHANGEOUT OPERATIONS

The instrument changeout operation differs from the stand-alone cryogen replenishment operation not only in that there are additional activities associated with the task of replacing instruments, but also in that the SIRTF dewar must be warmed to 300K. As discussed in Section 3.1.1, we feel that exposure of a cold telescope and instruments to the Orbiter or Space Station environment presents an unacceptable contamination risk. Hence our operations include warming the SIRTF dewar to 300K before performing the changeout and a subsequently longer cooldown period during the cryogen fill operation.

The additional time required for both changeout and cooldown extend the length of the Shuttle mission to close to the current maximum of seven days. Although it is planned to be able to extend missions beyond seven days in the future, we have attempted to develop a concept that would make it possible to complete the changeout and dewar fill within the current mission duration. To that end, we have paid particular attention to phasing the

task activities for the Shuttle-based changeout with crew rest periods and known EVA restrictions.

Since the mission duration is more critical on the Shuttle than it is on Station, we have focused our attention on that mission in Section 4.4.1. Section 4.4.2 briefly discusses the implication of performing the changeout on Station. The detailed operational sequence and timelines for Station-based changeout appear in Appendix A.

Assumptions used for Instrument Changeout Operation-

- The Shuttle crew has a twelve hour working shift followed by a twelve hour rest period. All crew members work the same shift; there is no crew activity during the rest period.

- The duration of an EVA is six hours maximum. Four hours are required to prepare for an EVA.

- SIRTF is the primary mission for the flight and other payloads will not receive significant attention during SIRTF EVA activities.

- Ground operations personnel will monitor and control long duration activities such as cooldown or transfer if they occur during crew rest periods.

4.4.1 Orbiter-based Instrument Changeout

Mission Scenario

The overall mission scenario for the instrument changeout on the Orbiter is essentially the same as the Orbiter-based cryogen replenishment activity shown in Figure 4-21. The Shuttle is launched into a 28.5 degree 400 km orbit carrying Orbital Replacement Units (ORU) in addition to the cryo ASE

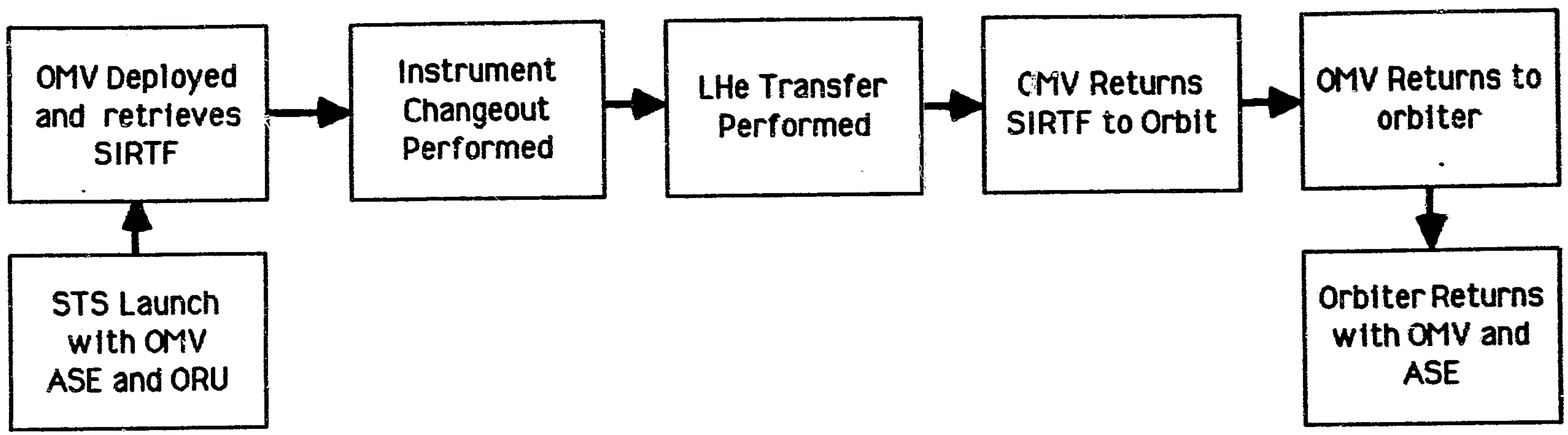

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Figure 4-21 Mission Scenario for Orbiter-Based Instrument Changeout

and OMV. The OMV is deployed and retrieves SIRTF. Internal heaters on the SIRTF cryogen tank and instruments have warmed SIRTF to 300K prior to the rendezvous with the OMV. The SIRTF is placed on the service structure and the electrical connections and transfer line are attached. The changeout and transfer are performed. The remainder of the mission proceeds as described in 4.4.2.

Hardware Configuration

The layout of the hardware in the Orbiter bay is shown in Figure 4-22. In this case, the OMV will most probably be stowed under SIRTF's working area in order to allow the RMS better access to the ORU and the aft end of the SIRTF dewar. The electrical layout is the same as described in Section 4.4.2. During instrument changeout, the dewar access door is swung 90 to 120 degrees from the closed position and allows complete access to the MIC. The crew member is positioned on the RMS work platform in any clocking position about the dewar axis that is required for access to the instruments.

Operations and Timeline

The operations sequence is shown in Figure 4-23. We will only go into detail about those operations that are different from the ones discussed for the Shuttle-based replenishment discussed in Section 4.3.2. The initial sequence is essentially the same as for the replenishment operation up until the SIRTF and OMV are berthed in the Orbiter bay. The transfer line and electrical umbilical are attached and the leak check of the transfer line is performed during this first EVA, before the instrument changeout tasks start. This eliminates the necessity for an additional EVA operation after instrument changeout.

- Dewar access door opened- The first operation of the second EVA is to unfasten the dogs holding the SIRTF dewar bottom shut. The RMS is used to swing the door up and into a stowed position where

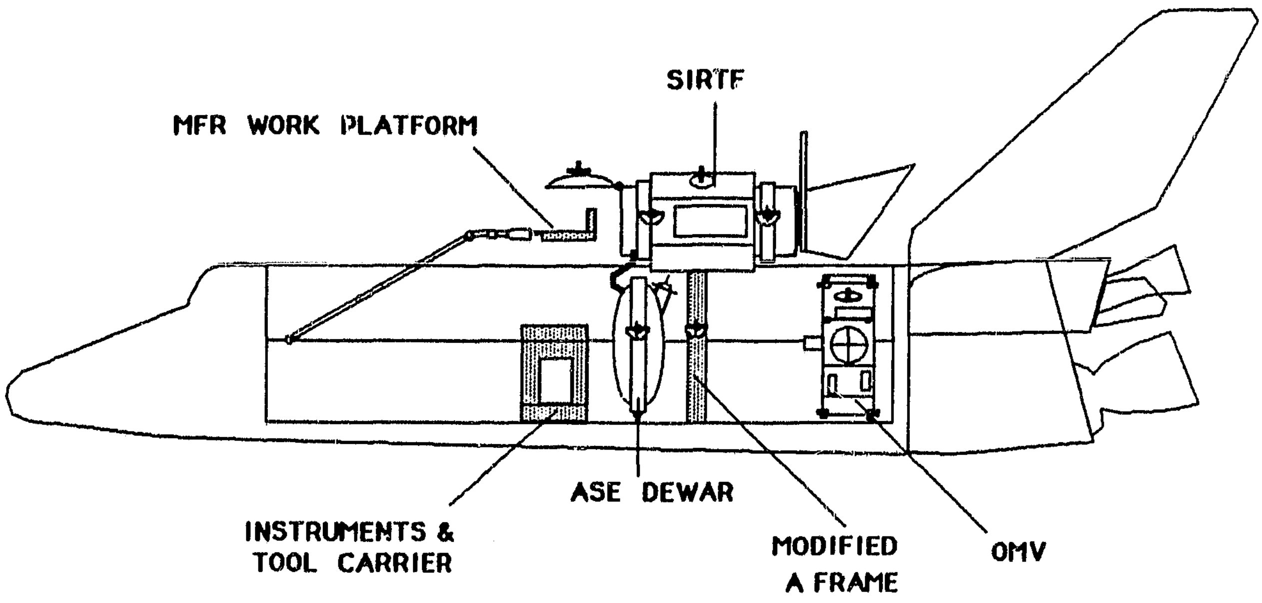

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Figure 4-22 Instrument Changeout Configuration on Orbiter

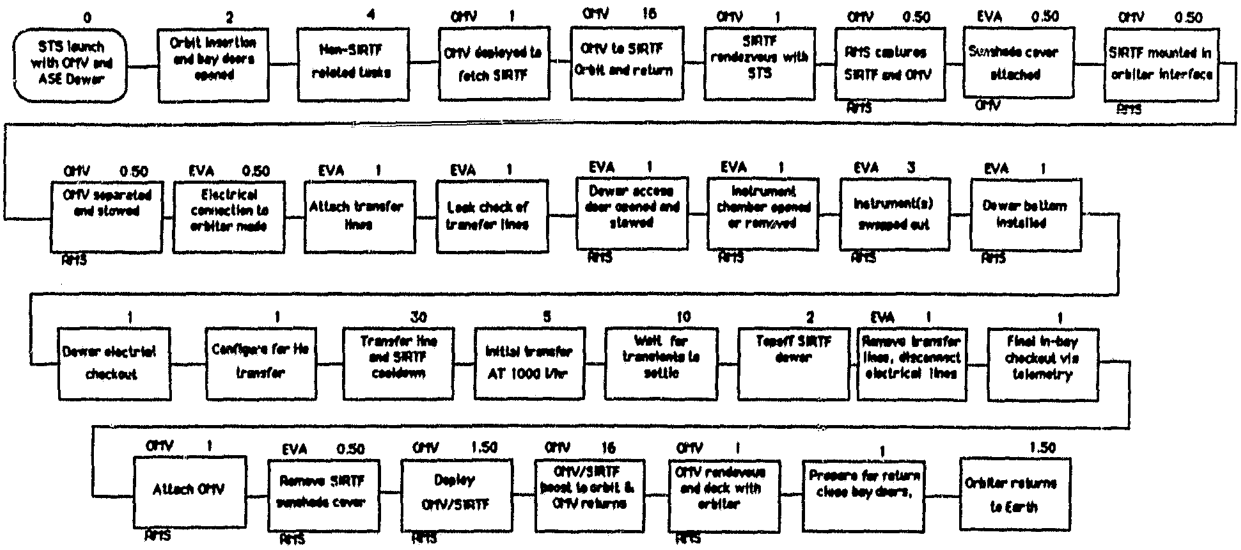

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Figure 4-23 Operations Sequence

it is safety clamped. One hour is assumed for EVA crew translation to the dewar and dewar opening and securing.

- Instrument exchange- A four hour period of the EVA is assumed for the instrument changeout operation. Two crew members are assumed for the operation; one crew member would work the changeout of the boxes internal to the dewar and the other would work the external box exchange simultaneously. The crew member working the external boxes would be available for intermittent support of the other crew member if need be. The RMS would be used to support the Manipulator Foot Restraint used by the crew member working inside the dewar.

  The mechanical, thermal and electrical interfaces of the instruments are be designed such that the changeout can be completed in this single EVA period. An additional EVA can be used as a contingency if the overall mission can be extended beyond seven days.

- Dewar access closed- Again the RMS would be used to assist the EVA for this operation. The dewar closure need only be adequate for structural support of the OMV reboost operation. A hermetic seal is not required.

- The remaining operations consist of the dear cooldown and helium transfer. The cooldown is performed in 30 hours, followed by 5 hours for the actual transfer. A 10 hour stabilization time is assumed to allow the instruments to complete their cooldown before the final topoff.

- In parallel with the cooldown and transfer operation, instrument electronic checks can be performed via telemetry.

- A third EVA is used to remove the transfer lines and remove the sunshade cover prior to final deployment of the OMV/SIRTF.

Timeline

The timeline for the changeout operation on the Orbiter is shown in Figure 4-24.

- The timeline shows that instrument changeout and replenishment of the warm SIRTF requires a 6.2 day mission and three EVA's. The EVAs on day 2 and day 3 of the mission are six hours each.

- The mission timeline is phased with crew rest periods and EVA preparation time. The entire changeout operation is shown to take place in one six hour EVA. This will impose severe design constraints on the interfaces of the instruments to the dewar. An additional EVA could be added in the fourth day of the mission to extend the amount of time available for changeout, but without other changes in the overall approach, this would extend the mission an additional 24 hours.

- Figure 4-25 shows the advantage of using of using the RMS to remove the sunshade cover remotely. By moving the third EVA to day 5 instead of day 6, the transfer line and SIRTF umbilical can be disconnected a day earlier. Then two crew members can deploy the OMV/SIRTF during the crew rest period. This would shorten the mission to 5.5 days but has the disadvantage that some work would be required of the crew during a normal rest period. This is the only instance where the use of a remote operation reduces the overall mission duration.

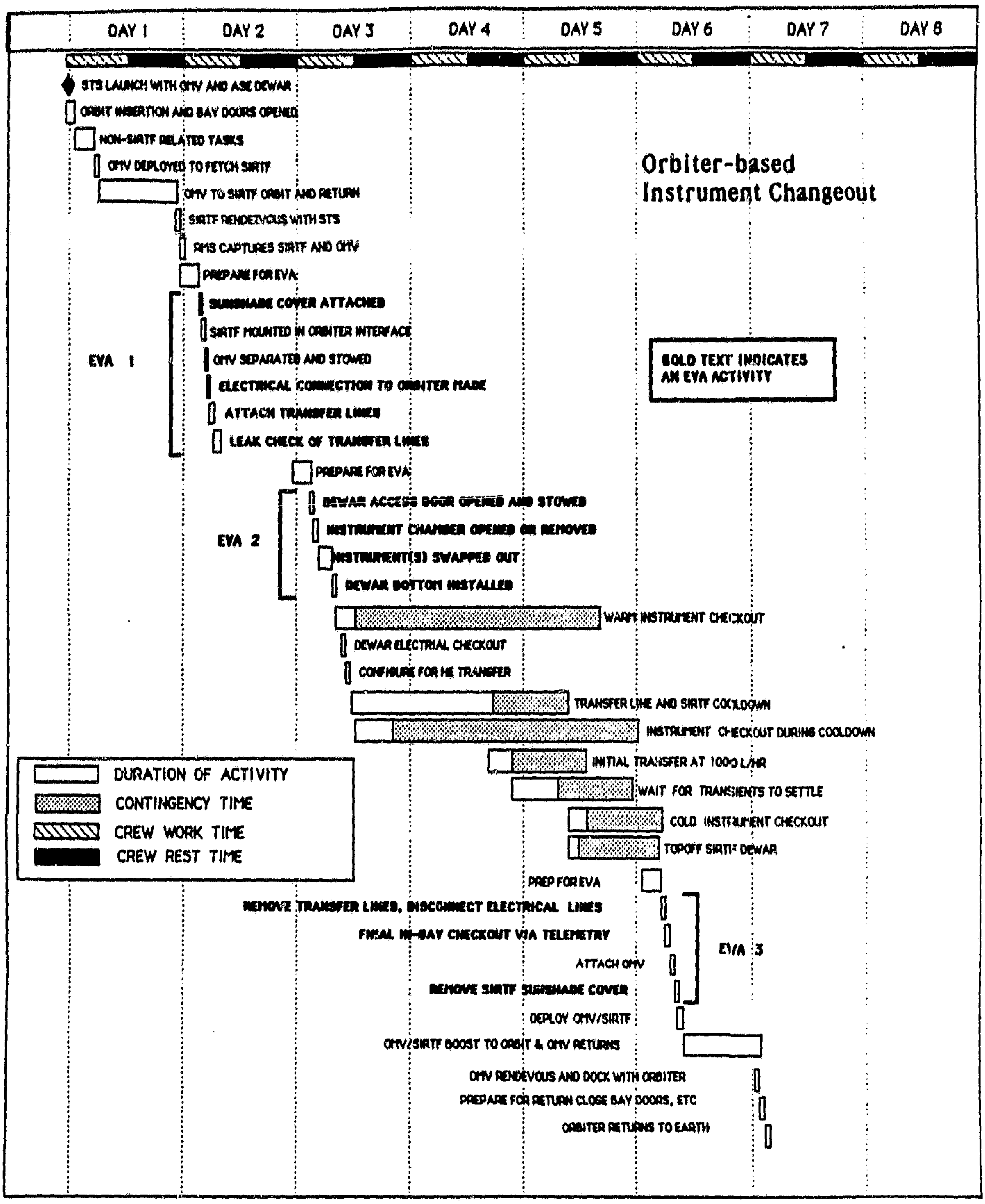

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Figure 4-24 Timeline for Orbiter-Based Changeout

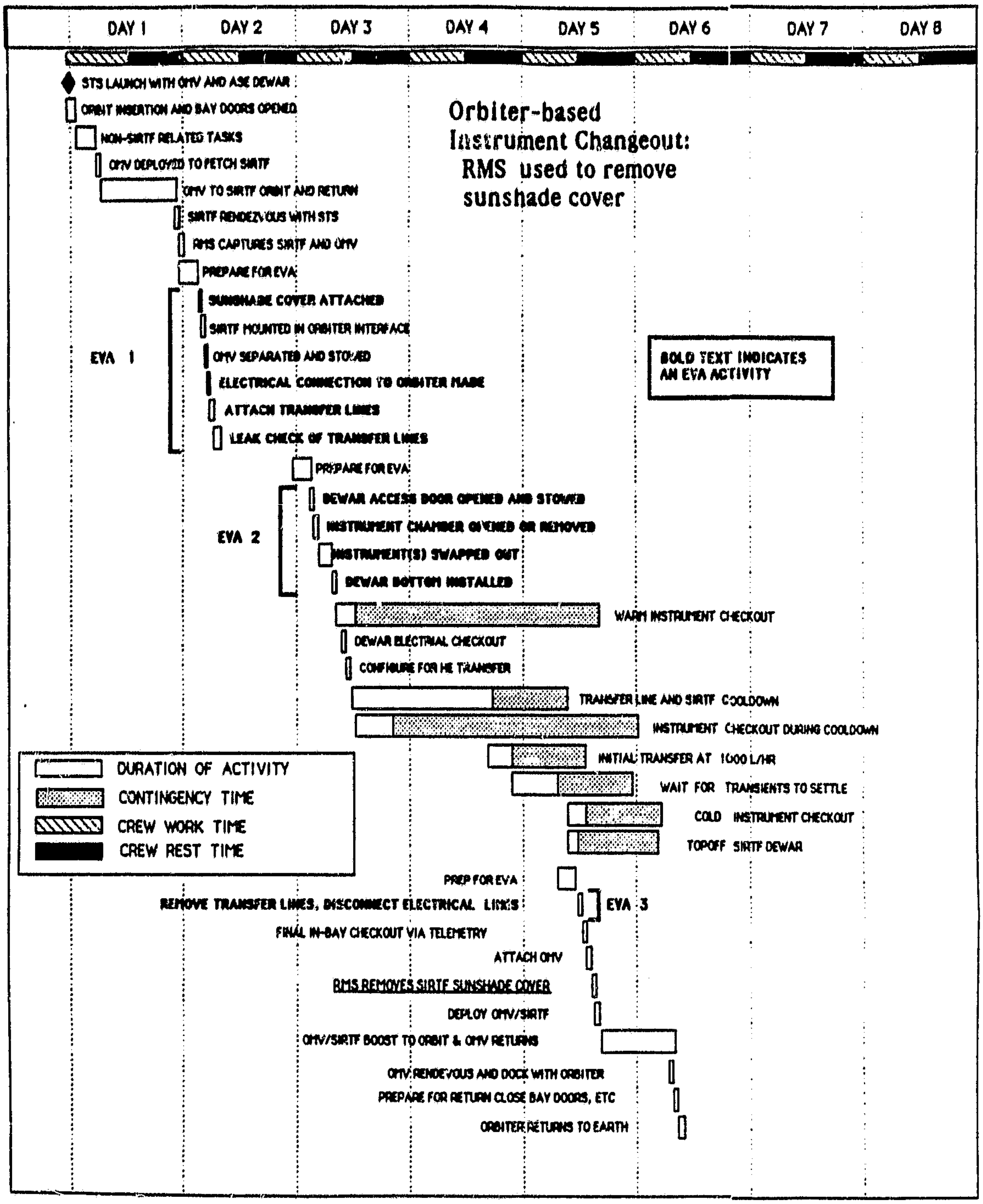

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Figure 4-25 Orbiter-Based Instrument Changeout:
RMS Used to Remove Sunshade Cover

4.4.2 Space Station-based Instrument Changeout

The overall mission for the changeout operation on Space Station is essentially the same as the replenishment mission described in Section 4.3.3. Rather than repeat the mission scenarios, hardware configurations and operational descriptions in their entirety, we will focus on the major differences between this mission and the Station-based replenishment. A complete description of the mission is contained in Appendix A.

The basic scenario for the changeout mission is the same as shown in Figure 4-13 for the cryogen replenishment. The ASE and the replacement instruments are transported to the Station via Shuttle during a routine service mission. The major difference is that now the larger 11,500 liter dewar is required since the SIRTF dewar will require cooldown from 300K.

The hardware configuration will be the same as described in Section 4.3.3, except that an ORU carrier will be required to house the instruments during the changeout. The MRMS will be used to support a crew member and the instruments during the actual exchange or installation of the instruments. All operations performed with the dewar access door opened must be conducted in an enclosed bay or tent that provides a protection against particle and molecular contamination. The advantage that the Station offers here is that the enclosed bays should be able to provide an environment that is more benign than the Shuttle bay.

Figure 4-26 shows the overall timeline for the changeout. Because the Station can provide around-the-clock crew shifts, the staging of the operations with the crew rest periods is not required so this timeline is shorter than that of the changeout mission of the Orbiter. The operation from the time of OMV launch to the return of SIRTF to operational orbit can take as little as 4.5 days. However, since the Station operations are not constrained by a maximum mission duration as was the Shuttle, there is no obvious need to compress the schedule. This means that the actual instrument

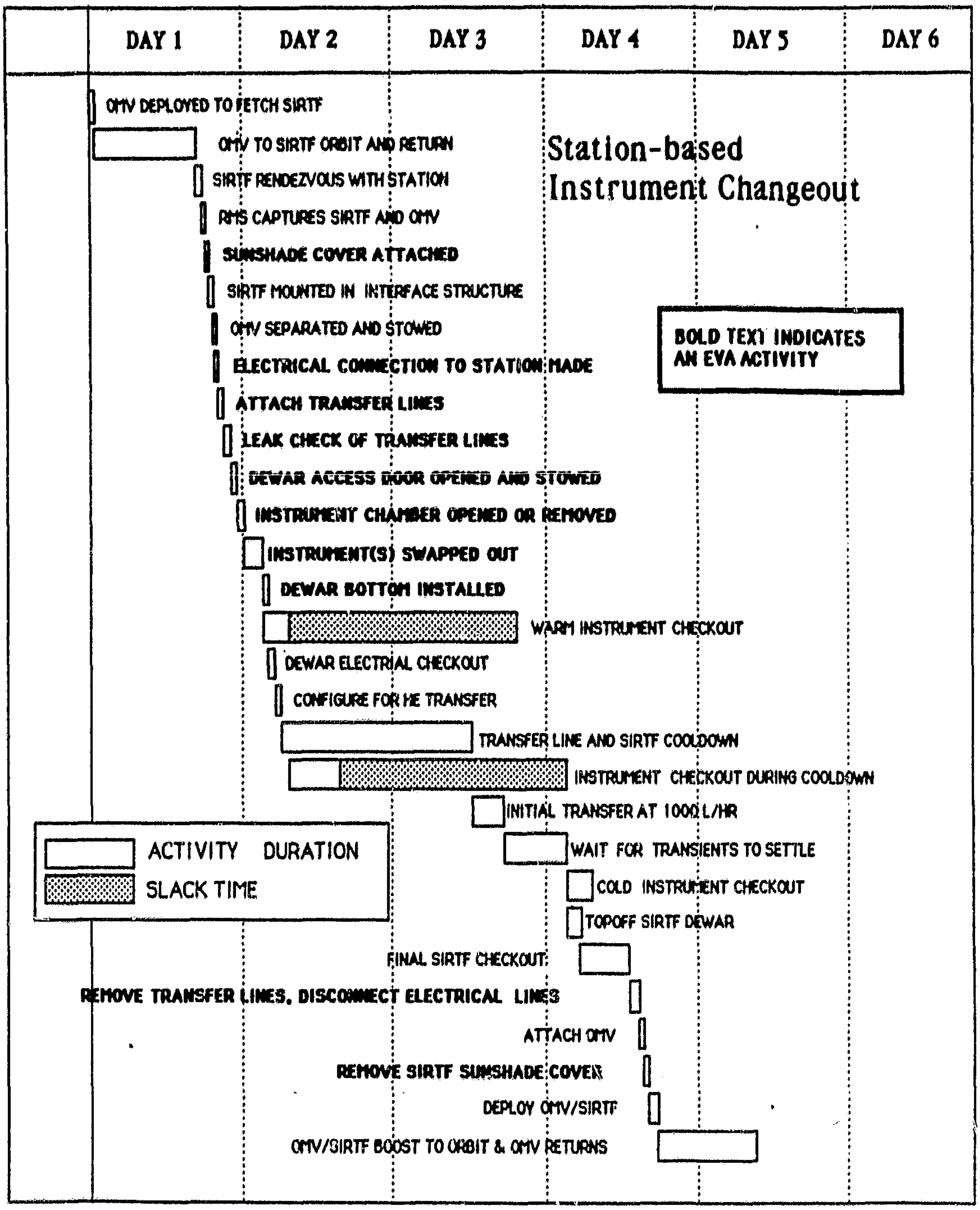

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Figure 4-26 Station-Based Instrument Changeout

changeout operations can be extended beyond the single 6 hour EVA shown in the timeline.

In summary, the changeout operation on Space Station offers some distinct advantages over performing the same operation on Shuttle :

- The Station bays or enclosures are potentially cleaner environments than the Shuttle bay and will probably offer better protection to the open dewar and instrument cavity.

- Without the schedule pressure of a limited duration mission, additional time and probably additional EVAs are possible for the actual instrument changeout. This will relax some of the instrument and facility design constraints that were necessary to optimize the changeout operation for the Shuttle mission. Of course, these constraints would still be carried if the Shuttle-based operation was to be considered a backup.

- Probably most important is that if there were difficulties encountered during the changeout or some facility anomaly occurred, Station can provide a safe storage area for SIRTF for essentially an indefinite period of time. This would permit extensive diagnostics to be performed without necessitating a return to earth.

Section 5
TECHNOLOGY DEVELOPMENT PLAN

The state of development of the critical technology elements is summarized in Figure 5-1. The list in the left hand side of the figure includes the major development items associated with the helium transfer and instrument changeout for SIRTF. Obviously the list is not complete, but it does include those items that are not in existence today. The items listed with Arabic numerals are necessary for the helium transfer operation, and those listed with Roman numerals apply to the instrument changeout. The numbers representing these items appear in the matrix on the right hand side of the figure.

The vertical axis of the matrix describes the state of the development of the item while the horizontal axis indicates its mission criticality. Hence an item that is shown in the upper left box, "feasible in theory" and "high" mission criticality has a high level of programmatic risk associated with it, while any item in the lower right hand corner, with "proven flight design" and "low" mission criticality, would represent very low programmatic risk.

This representation is useful to prioritize those items that must be addressed in early development planning in order to reduce overall programmatic risk. The object of the development plan is to move items from the upper right hand corner of the matrix towards the lower left through an orderly sequence of development design and testing.

The vertical axis spans the range of development status from proven flight design to theoretically possible. The divisions require a bit of explanation:

1	THERMOMECHANICAL PUMP
2	MECHANICAL PUMP
3	HI CONDUCTANCE VALVES
4	TRANSFER LINES
5	BAYONETS
6	MASS QUANTITY SENSOR
7	GAS FLOW METER
8	FLUID FLOW METER
9	LIQUID AQUISITION SYSTEM
10	HI CONDUCTANCE POROUS PLUG VENT
11	SUPERFLUID TRANSFER MODEL
I	EVA THERMAL CONTACTS
II	MLI BLANKET EDGE FABRICATION
III	VCS SHRINK FIT JOINT

	A	B	C
FEASIBLE IN THEORY	9 III	6 II	
WORKING LABORATORY MODEL	1 2 I 11		
BASED ON EXISTING NON-FLIGHT ENGINEERING	5 3	4	7 8
EXTRAPOLATED FROM EXISTING FLIGHT DESIGN	10		
PROVEN FLIGHT DESIGN			

hi ← criticality → lo

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Figure 5-1 Technology Development Matrix

- Feasible in Theory - An item is accepted as possible by the general community of experts, usually backed by analysis and a conceptual design, but not necessarily. This is not where the "blue sky" ideas go, however. Those ideas are off-scale on this axis.

- Working Laboratory Model - Just that. An item that has been shown to function on the laboratory scale goes in this category. The problems of flight qualification have not been addressed at this level.

- Based on Non-flight Engineering - Working units exist in ground applications but have not been modified for flight use as of yet. Full flight qualification is required.

- Extrapolated from Existing Flight Design - A unit of similar function and design has been flown before. This type of item could be qualified for flight by similarity. Only acceptance testing will be required on the item.

- Proven Flight Design - It has been done before and flown successfully.

The horizontal criticality scale is sort of gray but broadly breaks down in the following manner:

- High - The success of the mission is dependent on the success of the item. If these items failed, so would the mission. Redundancy would be provided for the function of these items in the actual mission. In the case of the development program, it would be wise to pursue parallel development for the function, e.g., simultaneously pursuing the thermomechanical and mechanical pumps.

- Medium - This range covers the arena of performance dependence. The overall mission performance is related to the performance of these items, but a successful mission can occur even if these items perform marginally. A non-existent mass flow meter would not cancel the mission, but knowing the difference between 80 percent and 100 percent fill is important.

- Low - Items in this range are usually considered part of the system, but provide engineering information only or have viable operational and functional work arounds during the actual mission.

ITEM 1:

PUMP SYSTEM, THERMOMECHANICAL

DESCRIPTION:

Thermomechanical system used to transfer He II from supply dewar to SIRTF.

STATUS:

Laboratory model of the thermomechanical pump system is currently under test at BASD. GSFC is also currently engaged in development of a pump for a zero-g experiment on Shuttle.

CRITICALITY:

A working pumping mechanism is highly critical to the in-orbit cryogen transfer mission. The overall programmatic risk is reduced since there are currently two options being pursued, both with reasonable chance of success.

APPROACH:

Demonstrate function of pump in one-g environment and measure performance parameters. Develop analytical model suitable for designing flight unit and verify with detailed testing of development unit. Full zero-g test combined with Items 2 and 9 should be performed on Shuttle test bed.

MILESTONES:

1985 - Operational test of T/M pump in one g at BASD.

1986 - 1 g test of T/M pump at GSFC

1989 - 0-g transfer test (combined with Items 2 and 9) on STS mission.

COST:

$250K Initial ground test

$5M Flight demonstration (combined with Items 2 and 9)

BP20AH1-1

ITEM 2:

PUMP SYSTEM, MECHANICAL

DESCRIPTION:

Mechanical pump system (probably centrifugal) for transfer of helium from supply dewar to SIRTF

STATUS:

Currently under development at NBS laboratories in Boulder, CO. Has been run successfully.

CRITICALITY:

The demonstration of a functional pumping mechanism for transfering helium is critical to the program. Programmatic risk is reduced since there are two pump types under development in parallel.

APPROACH:

Demonstrate function of pump in one-g environment and measure performance parameters. Develop analytical model suitable for designing flight unit and verify with detailed testing of development unit. Full zero-g test combined with Items 1 and 9 should be performed on Shuttle test bed.

MILESTONES:

1985 - Detailed testing of existing pump with He II at NBS.

1986 - Verification of pump design model.

1989 - 0-g transfer test on STS mission.

COST:

$250K Initial ground test

$5M Flight demonstration (combined with Items 1 and 9)

ITEM 3:

HIGH CONDUCTANCE VALVES

DESCRIPTION:

High throughput cryogenic valves are required to allow cooldown of warm dewar and fluid transfer rates of 1000 liters/hour. High conductance valves are required to permit adequate pump down rates of both the ASE and SIRTF dewar to maintain superfluid phases during the transfer process.

STATUS:

No work currently being performed. Design can be based on existing ball, gate, or butterfly valves.

CRITICALITY:

High mission criticality; there are no alternatives available. The programmatic risk is medium, since there exist several commercial candidates and the flight development can benefit from the work done on IRAS and COBE.

APPROACH:

Determine maximum acceptable impedance and leak rate using end-to-end transfer system model. Survey available commercial designs and select one for development. Modify as required and test for leak rate, reliability at 1.8K.

SCHEDULE:

9 Months

COST:

$400K

ITEM 4:

TRANSFER LINES

DESCRIPTION:

He transfer line that is EVA compatible and has acceptable heat leak.

STATUS:

Can be based on existing non-flight engineering.

CRITICALITY:

Medium to High mission criticality; a special direct insertion bayonet coupling might be used instead. Low programmatic risk since design would be a simple extrapolation of existing ground based transfer line design.

APPROACH:

Design using established techniques. Use end-to-end transfer system model to establish heat leak requirements. Demonstration unit could be added to coupling development program (Item 5).

MILESTONES :

See Item 5.

COST:

See Item 5.

ITEM 5:

EVA COMPATIBLE BAYONET COUPLINGS

DESCRIPTION:

Bayonet couplings suitable for operation by EVA crewmember to connect transfer line between ASE dewar and SIRTF.

STATUS:

Base on existing non-flight designs. JSC is preparing to let an RFP for a flight-qualified cryogen transfer coupling design and development.

CRITICALITY:

High mission criticality; there is no alternative to using a bayonet coupling. Medium to high programmatic risk since, although technically feasible, implementation for a man-rated system may be difficult and expensive.

APPROACH:

Develop coupling for helium and other cryogens. Deliver test units to ARC and JSC. Proceed to build SIRTF flight units.

MILESTONES:

1986 - JSC RFP issued

1987 - 1st test hardware delivered.

1989 - SIRTF flight coupling delivered.

COST:

$3M

ITEM 6:

HELIUM MASS QUANTITY SENSOR

DESCRIPTION:

A sensor that can measure the amount of He II in a dewar in a zero g environment. Needed to judge the progress and extent of completion of the fluid transfer. Very desirable in both SIRTF and ASE dewars.

STATUS:

Various techniques have been proposed, but not demonstrated. RFP for laboratory brassboard issued by JSC covers many cryogens. Unit developed by JSC may or may not meet STICCRS needs because of unique properties of He II.

CRITICALITY:

Medium mission criticality. Although an important adjunct to determining the course of the transfer operation, the lack of the sensor will only reduce the reliability of a 100 percent transfer. Analysis and perhaps thermometry can compensate somewhat. However, considering that an 80 percent fill on a service mission costing on the order of $30 M or more compared to a 100 percent fill given appropriate instrumentation suggests that effort and money spent here will see reasonable returns.

APPROACH:

Wait to see if current JSC brassboard effort will apply to He II. If it doesn't, begin similar ground-based brassboard for He II. Begin STS-based demonstration.

MILESTONES:

RFP 6/85

Contract Start 1/86

Contract Complete 12/87

COST:

$2M

ITEM 7:

GAS FLOW METER

DESCRIPTION:

Flow meter to measure gas venting rates of the supply dewar.

STATUS:

Current designs are available but are not compatible with the low impedance requirements of the high conductance vent lines of the supply dewar.

CRITICALITY:

This item is of low mission criticality since the data provided by it is primarily for diagnostic purposes only. Becomes more important if satisfactory mass quantity sensor is not available.

APPROACH:

Design around properties of He, flow range expected, and low pressure drop requirement. Possibly base on SL-2 IRT experience.

SCHEDULE:

2 Years

COST:

$2M

ITEM 8:

FLUID FLOW METER

DESCRIPTION:

Flow meter to measure rate of helium transfer from supply dewar to receiver.

STATUS:

Schemes based on second sound usable in laboratory.

CRITICALITY:

Low mission criticality if the mass quanity sensor is developed.

APPROACH:

Design for unique properties of He II, flow range expected.

SCHEDULE:

2 Years

COST:

$2M

ITEM 9:

LIQUID ACQUISITION SYSTEM

DESCRIPTION:

A device for ensuring that the pump is in contact with the He fluid in the supply dewar, and supplying fluid to the pump at the required flow rate.

STATUS:

Work is currently being performed on fluids other than He II, including water, hydrogen, oxygen and hydrazine. GSFC flight demonstration includes acquisition device based on surface tension. Alternate technique may deserve exploration.

CRITICALITY:

High mission criticality to achieve high transfer rate. Medium programmatic risk since superfluid film will probably support transfer at reduced flow rate.

APPROACH:

Surface tension device included with GSFC shuttle test bed. Explore alternate scheme(s) with lab tests.

MILESTONES:

1987 - Lab test of alternate device

1989 - Flight demonstration of surface tension device

COST:

$250K Lab tests

$4M Flight demonstration (combined with Items 1 and 2)

ITEM 10:

HIGH CONDUCTANCE POROUS PLUG

DESCRIPTION:

Used for fluid containment on the supply dewar, high conductance necessary for use with T/M pump and mechanical pump.

STATUS:

Theory seems to be developed and smaller plugs have been flown and characterized on IRAS, 2 Spacelab II experiments, and soon COBE. No current work being performed.

CRITICALITY:

High mission criticality; no reasonable alternative liquid containment method available. Medium programmatic risk since can be extrapolated from current designs.

APPROACH:

Design and procure plug for expected flow rate. Test in laboratory dewar with heater. Compare behavior with design predictions and resolve discrepancies.

SCHEDULE:

1 Year

COST:

$300K

ITEM 11:

END-TO-END SUPERFLUID TRANSFER MODEL

DESCRIPTION:

Detailed numerical time-dependent simulation of He II transfer system, including supply dewar, pump, transfer line, receiver dewar, and vents.

STATUS:

Core of model exists at BASD.

CRITICALITY:

High to medium mission criticality because needed for top-level system tradeoffs before detailed design can start.

APPROACH:

Add dewars, existing pump and vent models to existing model. Add convenience features, documentation to turn into user-friendly design tool.

SCHEDULE:

1 Year

COST:

$500K

ITEM I:

INSTRUMENT/DEWAR THERMAL JOINTS, EVA ASSEMBLED

DESCRIPTION:

A standardized thermal joint between the instruments and the dewar that can be easily made or separated by an EVA crewmember during the instrument changeout operation.

STATUS:

Repeatable thermal joints at He II temperatures demonstrated and quantified in BASD lab tests.

CRITICALITY:

High mission criticality for changeout. Thermal testing and EVA simulations required to standardize design for instruments.

APPROACH:

Design joint for EVA compatibility. Test forces, torques required. Test thermal performance at 1.8K after each of several mate/demate cycles.

SCHEDULE:

1 Year

COST:

$300K

ITEM II:

MLI BLANKET EDGE FABRICATION

DESCRIPTION:

A separable joint in the multilayer insulation (MLI) blanket at the cylinder/dome interface inside the SIRTF dewar that allows the bottom of the dewar to be opened for MIC access. Must withstand handling during system integration and instrument changeout.

STATUS:

No current work being done. Initial design concepts presented in BASD STICCRS Final Report.

CRITICALITY:

Medium mission criticality since most failure modes will result in mission lifetime degradation, not mission failure.

APPROACH:

Design and build short cylindrical test unit of full diameter. Test handling properties, gap with axis vertical and horizontal. Test thermal conduction. Combine with Item III.

MILESTONES:

1 Year (Items II and III combined)

COST:

$2M (Items II and III combined)

ITEM III:

VCS SHRINK FIT JOINT

DESCRIPTION:

Mechanical/thermal circumferential joint in VCS's of SIRTF dewar that separates during dewar opening for instrument access.

STATUS:

Initial design concept and analysis complete during STICCRS study.

CRITICALITY:

High mission criticality since failure could preclude closing the dewar after instrument changeout. The approach shown in this report appears feasible but requires a demonstration model of the same general dimensions as the flight unit to be built and tested for producibility, reliability and determination of handling characteristics.

APPROACH:

Full scale demonstration of this interface should be assembled and tested. Do in combination with Item II.

MILESTONES:

See Item II.

COST:

See Item II.

APPENDIX A

SPACE STATION-BASED SERVICING OF SIRTF

This appendix describes the SIRTF cryogen replenishment and instrument changeout missions on Space Station. The scenarios, operations, and timelines are presented for both missions. The facilities and services that are expected to be available from Station are mentioned, as is a summary of the Airborne Support Equipment (ASE) to Station interfaces.

For Space Station based operations we have assumed the IOC Reference Configuration per JSC-19989, the "power tower" configuration, for the Station capability baseline. This was for convenience in communication; the mission description and timelines are not sensitive to the final configuration except for the following assumptions:

- Orbiter-style rail and keel mounting structures will be available,
- An enclosed bay, providing contamination protection, will be available,
- The Mobile Remote Manipulator System (MRMS) or equivalent will be available,
- The Orbital Maneuvering Vehicle (OMV) will be available from station,
- Power and data buses will be available both on the structure and in the inhabited module, and
- Two month or longer storage of the ASE dewar with continuous automated monitoring will be possible.

- EVA will be available under the same constraints as Shuttle-based EVAs.

SPACE STATION-BASED REPLENISHMENT OPERATIONS

Mission Scenario

The top level scenario for the Station-based replenishment operation is shown in Figure A-1. Here, the ASE is transported to the Space Station during one of the routine service missions that are scheduled to occur on two month intervals. After docking at Station, the Station MRMS removes the ASE dewar from the Orbiter bay and carries it to an interim storage area. This storage area will probably be the "tank farm" located on the lower keel, above the inhabited modules.

The ASE dewar will be stored here for up to two months awaiting the arrival of SIRTF. Sometime during this two month period, an OMV will be dispatched from Station to fetch SIRTF. The OMV/SIRTF will rendezvous with Station and the SIRTF will be brought to a service hanger on the lower keel for the transfer operation.

After the transfer operation is complete, the SIRTF will be returned to 900 km orbit by an OMV and the ASE dewar will be returned to storage to await the next available Shuttle slot for the return trip to earth.

There is nothing critical about the overall schedule, except that manifesting of the ASE on a supply mission occur within a two month window of the retrieval of SIRTF.

Hardware Configuration

The probable locations of the storage site for the ASE dewar and the transfer operation on Space Station are shown in Figure A-2. After the ASE dewar

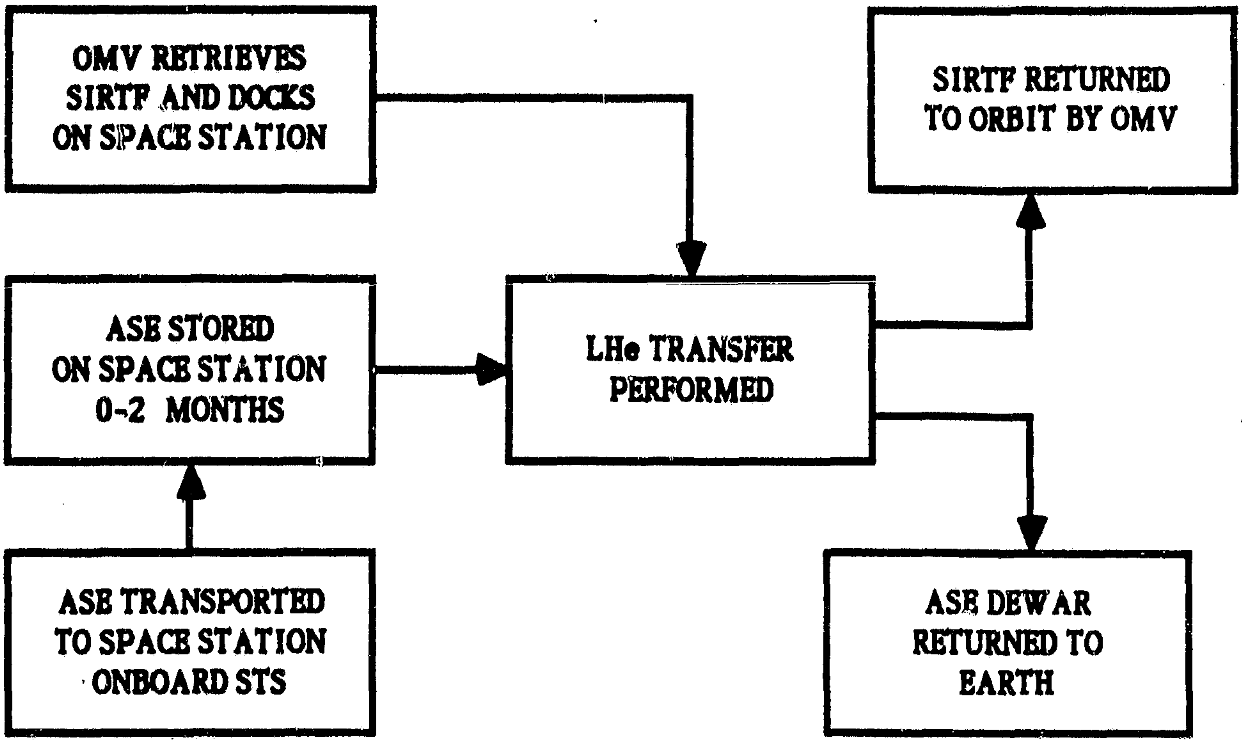

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Figure A-1 Space Station-Based Replenishment Scenario

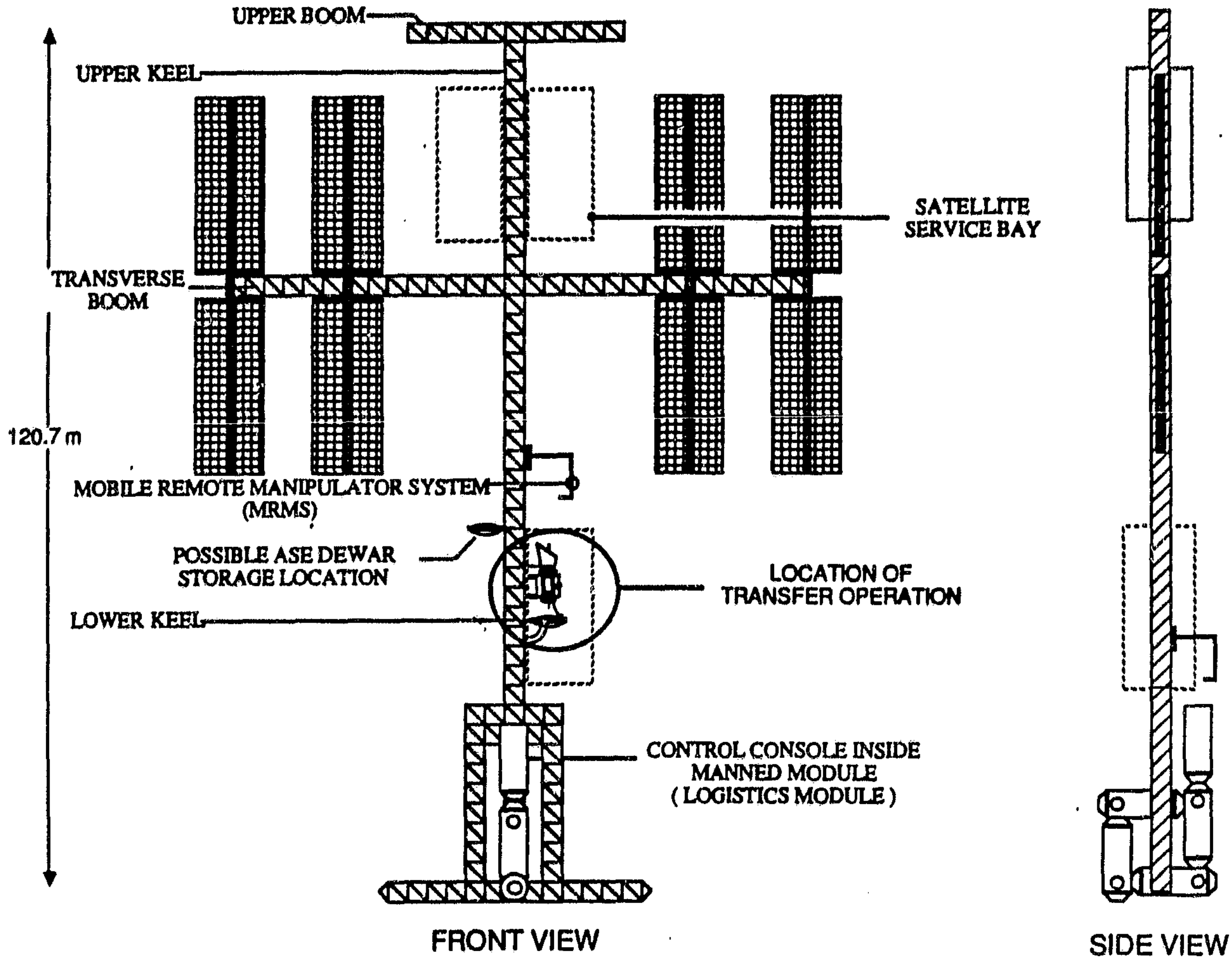

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Figure A-2 Storage and Transfer on Space Station

is transported to the Space Station by the Orbiter on a routine supply mission, the Station MRMS will remove it from the Orbiter bay. Alternately, the ASE dewar is provided with two opposing grapple fixtures that permit the RMS to pick the dewar out of the bay and hand it off to the Station MRMS. The MRMS then moves along the station structure to the lower keel. There the dewar is mounted on shuttle-style longeron mounts that are attached to the keel structure. The ASE dewar is designed with its own external thermal control finishes and does not have to be stored in any sort of thermal enclosure.

The dewar electronics are attached to the Space Station data and power bus to allow monitoring of the dewar health during the storage periods. We have assumed that an automatic monitoring procedure would be used for the the dewar that would sound an alarm if an over-limit condition occurred but otherwise would not require attention by the crew.

Prior to the arrival of SIRTF, the MRMS would move the ASE dewar into the Refueling Bay, also located on the lower keel. After being separated from the OMV, SIRTF would be also brought into the Refueling Bay, where the transfer operation would take place. The configuration of the ASE and SIRTF during the transfer operation is shown in Figure A-3. The SIRTF and the ASE dewar are both mounted on longeron mounts as they would be in the Orbiter bay. The configuration allows a transfer line that is less than 2 m in length.

The electrical power and command lines to SIRTF are over hard line from the external ASE electronics, which in this case are hooked to the Space Station power bus and data bus as shown in the simplified block diagram in Figure A-4. The ASE Command Console and internal electronics are located inside the Logistics Module and communicate with the external electronics via the Station data bus.

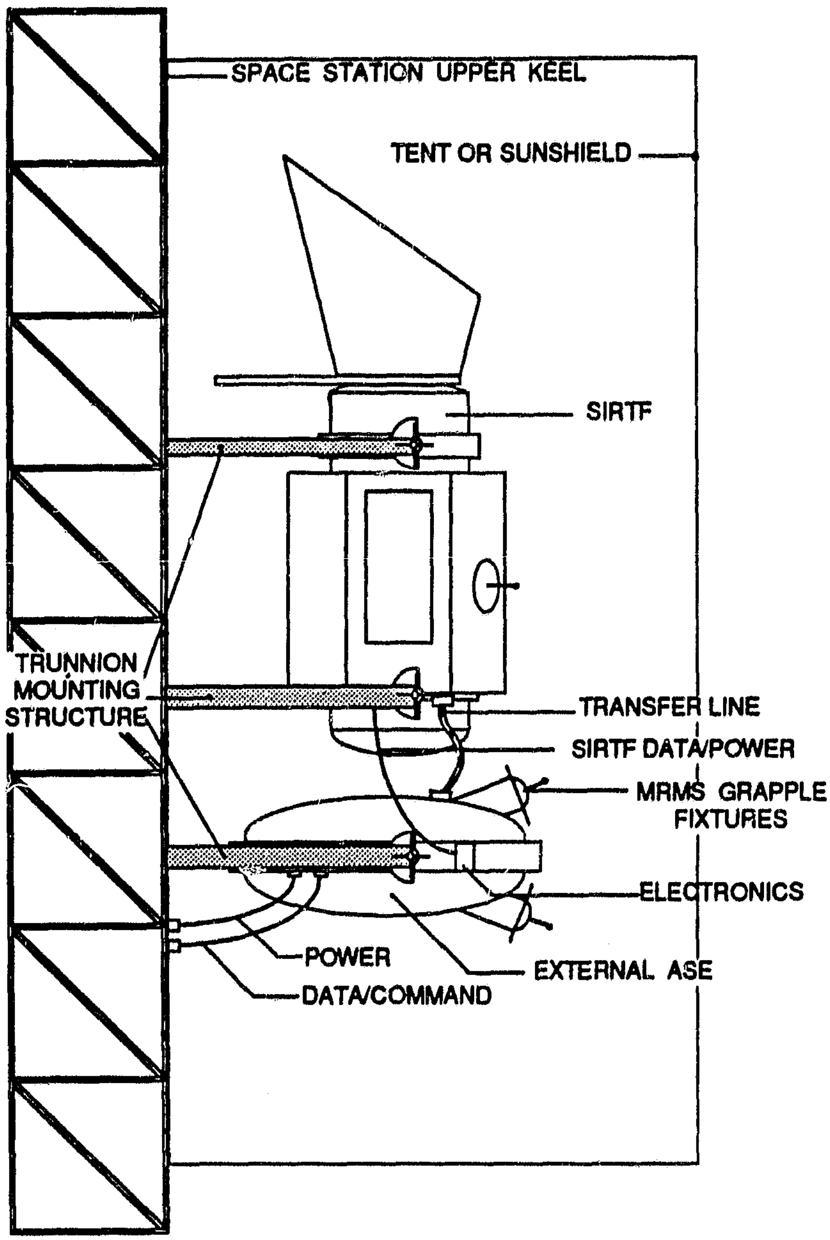

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Figure A-3 Configuration for Replenishment on Space Station

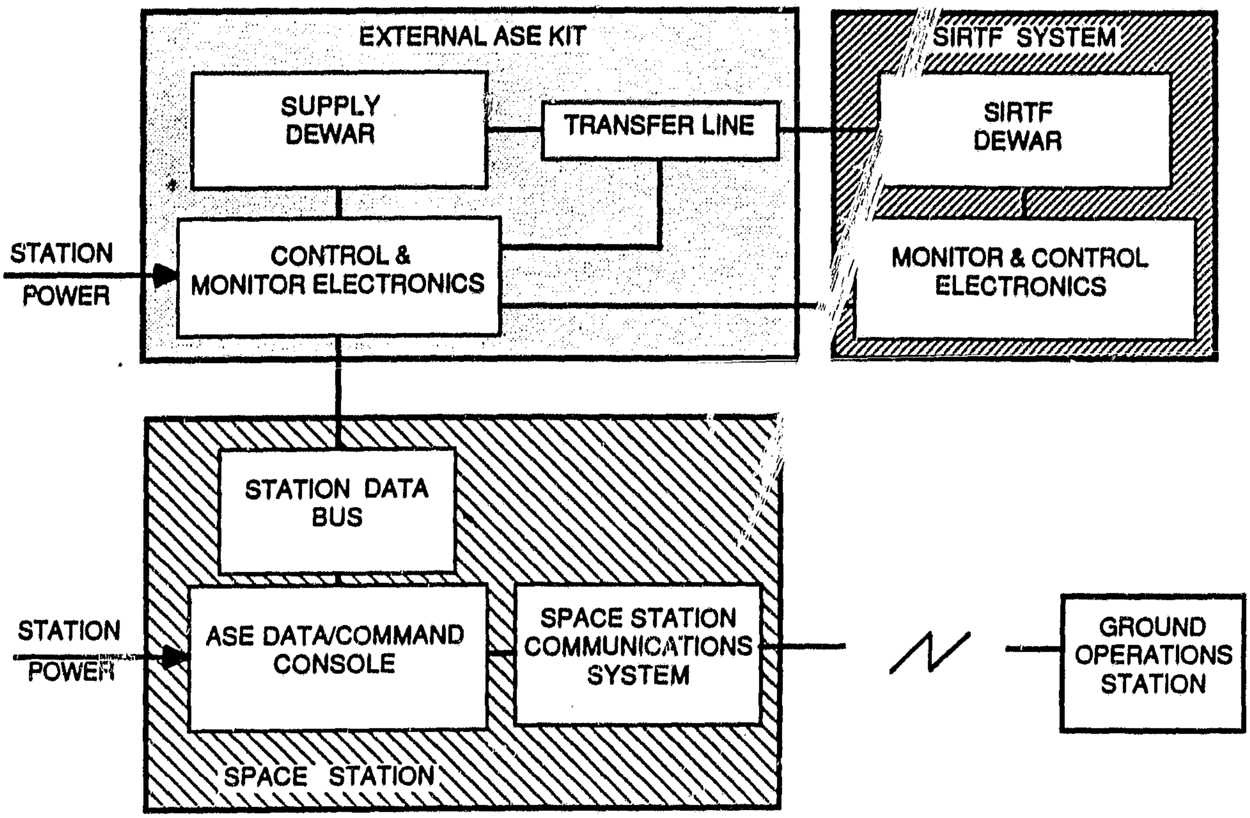

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Figure A-4 ASE System Configuration on Space Station

Operational Sequence and Timeline

A flow diagram of the operations for the replenishment activity onboard Space Station is shown in Figure A-5. The numbers in parentheses refer to the times required for the task if SIRTF starts the replenishment operations dry. Otherwise the numbers refer to the times associated with starting with a 2 K SIRTF dewar.

The timelines for the operations appear in Figures A-6 and A-7. The first timeline assumes that the SIRTF is still wet with helium at the start of the operation; the second assumes that SIRTF has been depleted of helium and achieved a tank temperature of 150 K. In the first case, the cooldown time is one hour and refers to cooling the transfer lines only. There is no time required for instrument stabilization or topoff. The second case requires a 20 hour dewar cooldown plus stabilization and topoff.

Discussion of the Operations

The operations depicted in Figure A-5 are summarized below:

- OMV to retrieve SIRTF - The schedule for OMV to capture and return SIRTF to the Orbiter allows 24 hours.

- Relocation of ASE dewar - The ASE dewar is moved from its storage area to the refueling bay and connected to the Station power bus and Data bus.

- SIRTF docking - The MRMS is used to capture the OMV/SIRTF, the two are separated and SIRTF placed in the refueling bay. The OMV is moved around refueling area for refueling and battery recharge.

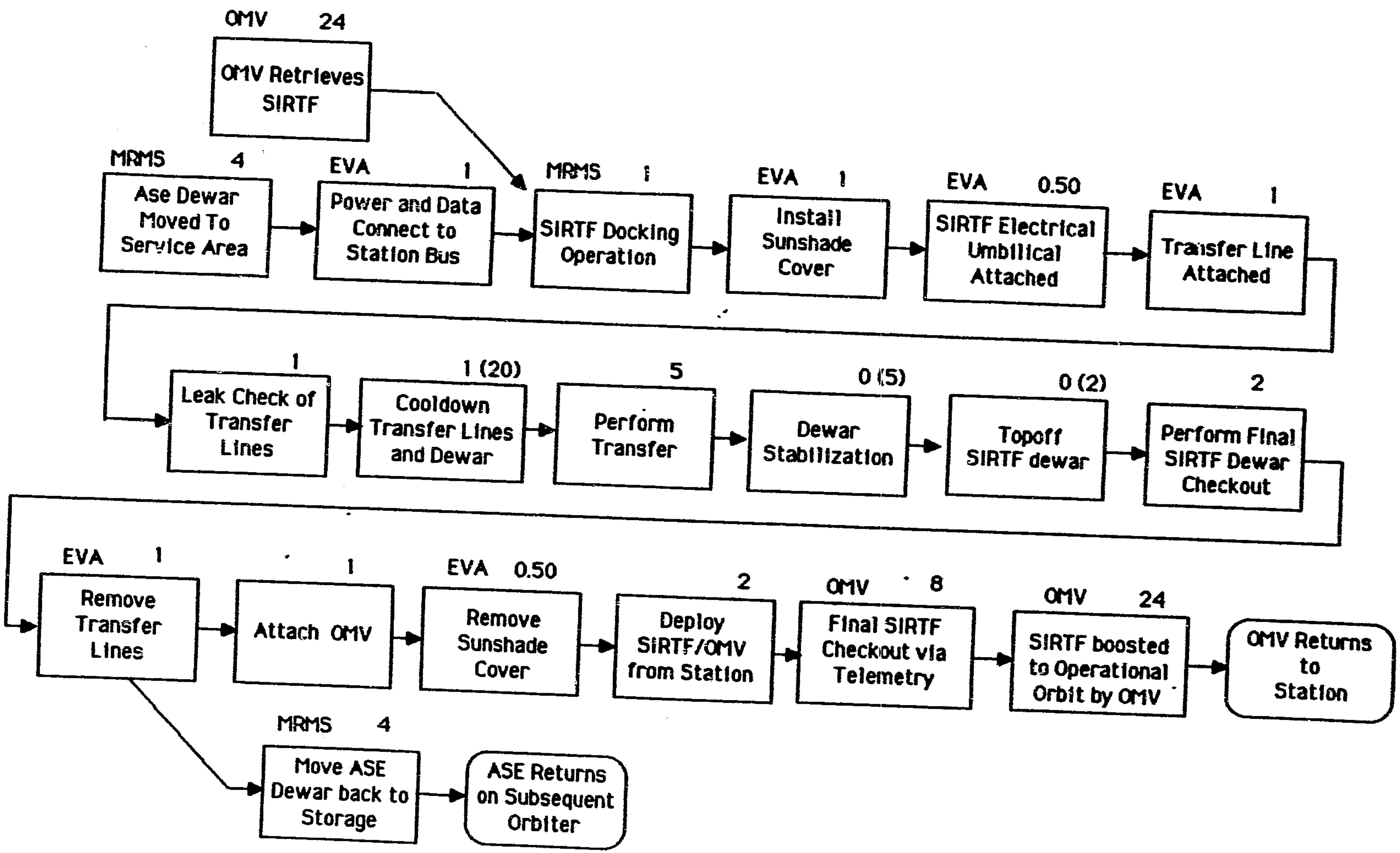

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Figure A-5 Operations for Station-Based Replenishment of SIRTF

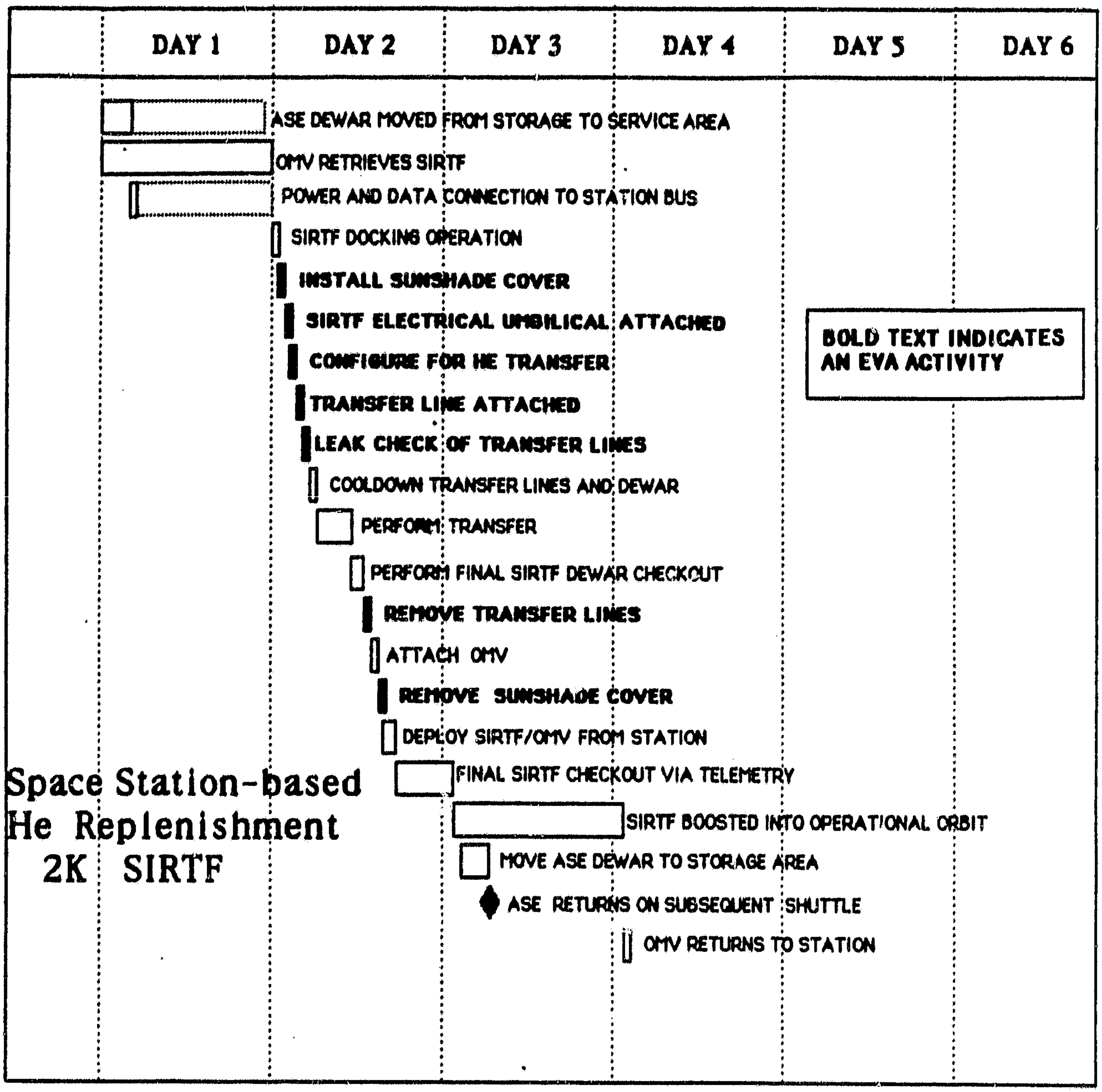

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Figure A-6 Timeline for Station-Based Replenishment of Cold SIRTF

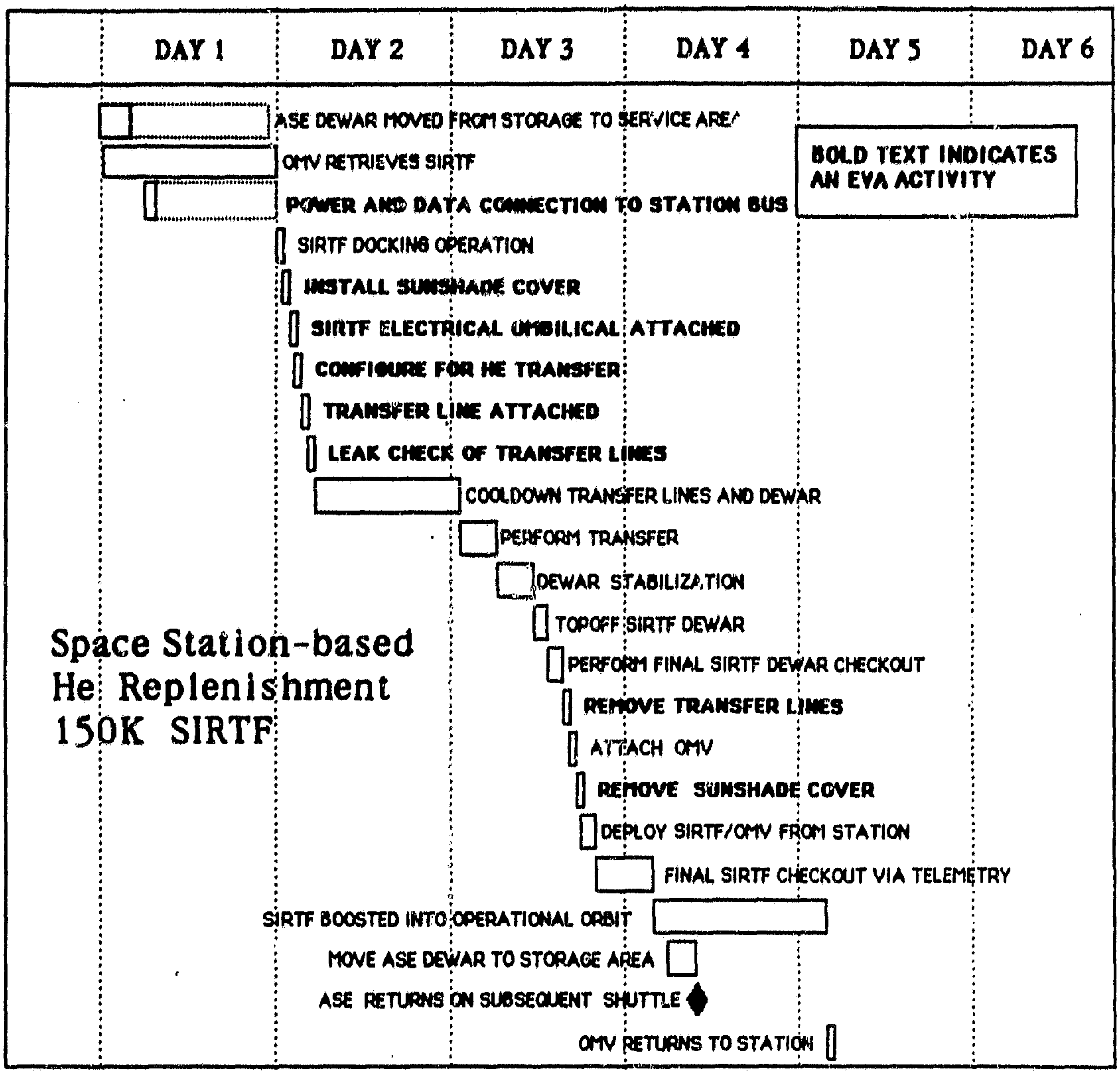

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Figure A-7 Timeline for Station-Based Replenishment of Warm SIRTF

- Sunshade cover attached - EVA is assumed for the task of covering the external aperture of the sunshade with a protective contamination cover. It would also be possible to use the MRMS to install a suitably designed cover. This would eliminate the need for this EVA.

- Electrical connections - The umbilical from the ASE dewar to the SIRTF is connected at this time. EVA is assumed. A remote connection could be set up such that connection occurred when the SIRTF was set in its cradle.

- Configure for transfer - Preliminary electrical check of the SIRTF system umbilical, valve status, thermometry and general status of the transfer system.

- Attach transfer lines - The line is removed from its storage position on the ASE dewar, interfaces are inspected, and the line is installed. This is the most difficult operation to perform remotely.

- Leak check of interconnects - The transfer line bayonets are checked for leaks by an external helium source or by the supply dewar boiloff. A hand held or RMS held mass spectrometer could be used for this operation. As with the Orbiter operation, this EVA would probably continue until the leak check was complete to allow inspection or treatment of a suspect leak without the delay associated with resuiting in the EMU's.

- Cooldown - At this point the transfer process would start and the cooldown of the transfer lines would be performed. If the SIRTF was depleted of helium to start with, then the cooldown would continue for 20 hours until liquid started to collect in the receiver dewar.

- Transfer of Helium - The transfer should take less than five hours at the anticipated 1000 liter/hour rate using the thermo-mechanical pump.

- Thermal Stabilization - In the event that the dewar was initially dry, it would be necessary to allow the instruments to continue to cooldown until the dewar boiloff stabilized. This time depends strongly on the instruments internal thermal design and could range from 5 to 24 hours, depending on initial temperatures. This time would be used for various health checks of SIRTF including instruments checks if the system is configured to allow them.

- Topoff - Again, in the case of starting with a dry dewar, the final cooldown of the instruments would consume a small portion of the helium transferred initially. This would be replenished by a topoff operation.

- Final checkout - A checkout of the transfer operation is performed, valve positions, temperatures, boil off rates are monitored.

- Remove transfer lines - EVA is used to remove the transfer lines and secure them to the ASE dewar.

- Attach OMV - The MRMS moves the OMV from its berth and attaches it to SIRTF.

- Remove sunshade contamination cover - EVA is baselined for this but remote operation is possible.

- Deploy OMV/SIRTF - the pair are released by the MRMS.

- Final checkout via telemetry - A final health check of the SIRTF system can now be performed via telemetry. This is the final

opportunity to elect to abort the orbit transfer operation and maintain the SIRTF on Station or bring it back to earth. In the event of an abort, the OMV would be separation and stowed and the abort procedures discussed in 4.2 would be initiated.

- Orbit transfer and insertion - This operation has been allowed 24 hours.

- OMV returns to Station - OMV is captured by the MRMS and returned to its storage bay.

- ASE moved back to storage area - The ASE is returned to storage until the next available Shuttle back to earth.

Discussion of the Timelines

The timelines for the Station-based operations are not as critical as those for the Orbiter-based transfer since there is no pressure from a time limited mission to optimize the schedule. The main comment to make therefore is that these timelines represent the minimum amount of time necessary to perform the transfer. However, there is no reason why the operations cannot be conducted in a more leisurely fashion. The minimum time for the the transfer to a wet SIRTF is 74.5 hours, including the retrieval and return to orbit by the OMV. The minimum time for the transfer to a wet SIRTF is 98 hours under the same condition.

SPACE STATION-BASED INSTRUMENT CHANGEOUT

Mission Scenario

The overall mission for the changeout operation on Space Station is essentially the s e a the replenishment mission shown in Figure A-1. The major dif ence is that now the larger 11,500 liter dewar is required since

the SIRTF dewar will require cool down from 300 K. The ASE and the change-out units are transported to the Space Station during one of the routine service missions that are scheduled to occur on two month intervals.

After docking at Station, the MRMS removes the ASE dewar from the Orbiter bay and carries it to an interim storage area, probably the "tank farm" located on the lower keel, above the inhabited modules. The ASE dewar will be stored here for up to two months awaiting the arrival of SIRTF.

Any Orbital Replacement Units (ORUs) will probably be mounted in a support cradle for the Shuttle flight to Station. This cradle would provide thermal control and a contamination free environment for the instruments. It would be moved onto Station from the Orbiter and transported by the MRMS to the Satellite Storage Bay until needed for the changeout operations.

Sometime during the next two months, an OMV will be dispatched from Station to fetch SIRTF. The OMV/SIRTF will rendezvous with Station and the SIRTF will be brought to a service hanger for the changeout operation. Since the contamination requirements for the changeout operation are tight, the Satellite service bay would be the most likely site for the changeout operation. Presumably, the ASE dewar would also be moved to this same site for the post-changeout transfer operation rather than transport SIRTF to the lower keel of Station in order to use the Refueling Bay.

After the transfer operation is complete, the SIRTF will be returned to 900 km orbit by an OMV and the ASE dewar and ORU cradle will be returned to storage to await the next available Shuttle slot for the return trip to earth.

Hardware Configuration

For instrument changeout, the hardware configuration will be the same as described for the transfer operation, except that an ORU carrier will be required to house the instruments during the changeout. The MRMS will be

used to support a crew member and the instruments during the actual exchange or installation of the instruments.

All operations performed with the dewar access door opened must be conducted in an enclosed bay or tent that provides a protection against particle and molecular contamination. The advantage that the Station offers here is that the enclosed bays should be able to provide an environment that is more benign than the Shuttle bay.

Operational Sequence and Timeline

Figure A-8 shows the overall timeline for the changeout. Because the Station can provide around-the-clock crew shifts, the staging of the operations with the crew rest periods is not required so this timeline is shorter than that of the changeout mission of the Orbiter. The operation from the time of OMV launch to the return of SIRTF to operational orbit can take as little as 4.5 days. However, since the Station operations are not constrained by a maximum mission duration as was the Shuttle, there is no obvious need to compress the schedule. This means that the actual instrument changeout operations can be extended beyond the single 6 hour EVA shown in the timeline.

Summary

In summary, the changeout operation on Space Station offers some distinct advantages over performing the same operation on Shuttle:

- The Station bays or enclosures are potentially cleaner environments than the Shuttle bay and will probably offer better protection to the open dewar and instrument cavity.

- Without the schedule pressure of a limited duration mission, additional time and probably additional EVAs are possible for the

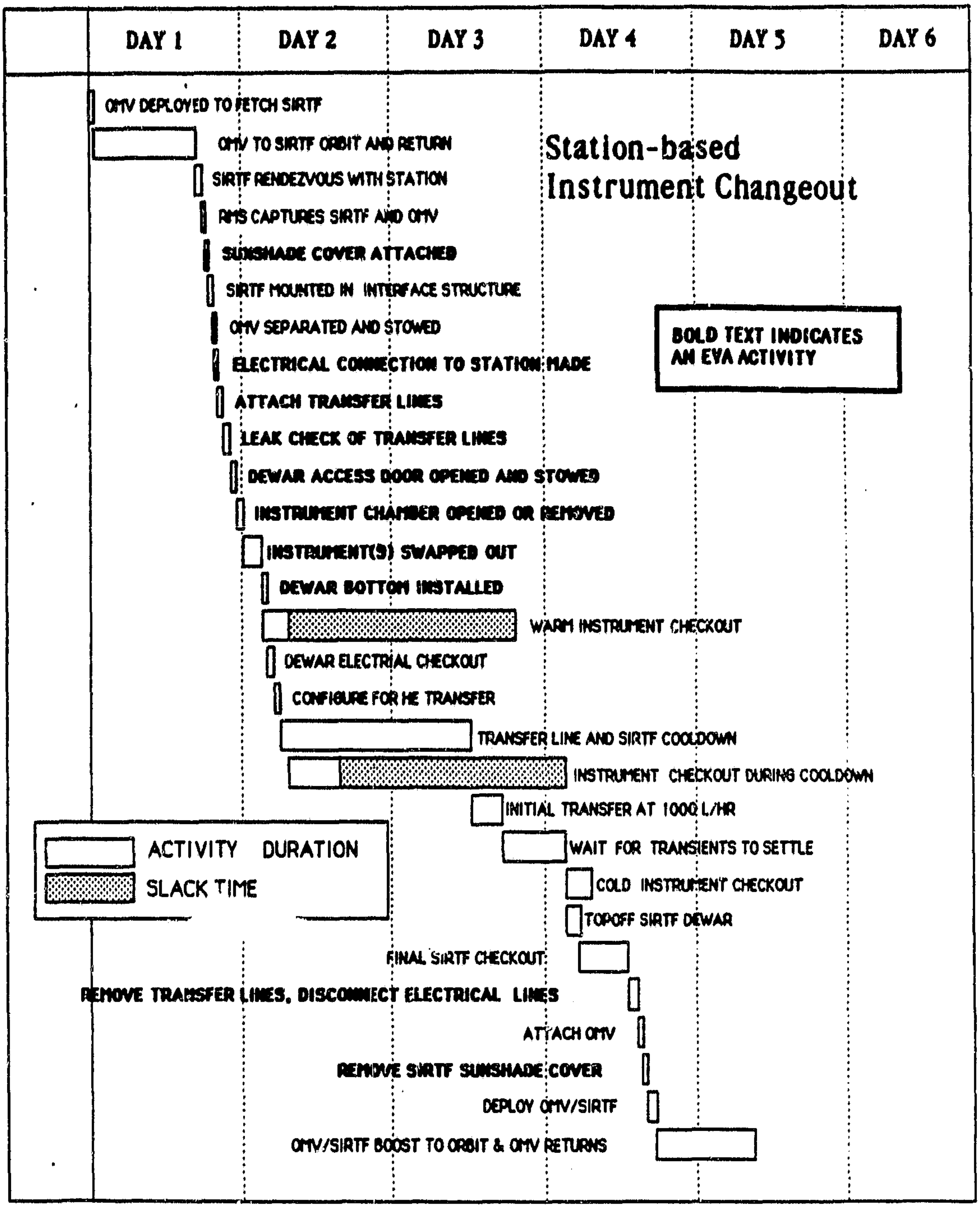

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Figure A-8 Station-Based Instrument Changeout

actual instrument changeout. This will relax some of the instrument and facility design constraints that were necessary to optimize the changeout operation for the Shuttle mission. Of course, these constraints would still be carried if the Shuttle-based operation was to be considered a backup.

- Probably most important is that if there were difficulties encountered during the changeout or some facility anomaly occurred, Station can provide a safe storage area for SIRTF for essentially an indefinite period of time. This would permit extensive diagnostics to be performed without necessitating a return to earth.

Interfaces

- The ASE dewar uses the 3-point longeron mounting scheme in the Orbiter bay. Presumably, Station will be able to provide a mechanical interface equivalent to the sill and keel fittings of the Orbiter bay. Two RMS grapple fixtures are provided on the dewar to allow transfer to Space Station MRMS by the Orbiter RMS if required.

- The ASE dewar interfaces to the Station data bus via the station provided interface system. There will be data bus interface ports available on the keel, in the logistics and other modules and presumably in the satellite service bay or the refueling bay. The data bus bus may be hardwire, fiber optic or RF based but in any case will require a standard interface box on both the dewar and control console sides.

- The SIRTF dewar would be mounted to the Station on Shuttle longeron fittings using either the three or five point mounting scheme. The transfer operations would be performed in the refueling bay. This bay must provide contamination protection from the general station outgassing and particulate environments.

- The changeout operation will have tighter contamination control requirements than the replenishment operation. A Level 300 environment should be considered an absolute minimum. This may require that the changeout be performed in the Satellite Service Bay rather than the Refueling Bay.

- The ASE dewar external thermal finish will have an α/ϵ of 0.20-0.30. In order to maintain main shell temperatures below 310 K inside the refueling bay, the total power dissipation in the service area enclosed by the bay must be below 0.5 kW. The ASE dewar can be stored on the station keel outside of a bay or tent until the time of the actual transfer operation.

- The peak power requirements of the ASE and SIRTF during the transfer operations would be 200 watts. This is assumes multiple, simultaneous valve actuation, which is rarely the case. Normally, the system would require less than 100 watts for transfer and monitoring operations. Power would be provided by the Station power bus.

- The replenishment mission requires a total of two EVA's, the duration of the first is six hours, the second is four hours. An additional EVA crew member is assumed for data monitoring and RMS manipulation.

- The changeout and subsequent replenishment requires three EVAs of approximately six hours each. EVA support should be assumed for the 4.5 day duration of the changeout operation.

APPENDIX B

MODELING OF SUPERFLUID HELIUM TRANSFER

The following manuscript was presented at the Superfluid Helium Transfer in Space Workshop, Boulder, Colorado, August 20-21, 1985. It will appear in a special issue of Cryogenics devoted to the workshop. This work was sponsored by BASD, and is included here for the convenience of the reader.

MODELING OF SUPERFLUID HELIUM TRANSFER

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ABSTRACT

A one dimensional model for the flow of He II is applied to a transfer line with flow driven by a thermomechanical pump. The thermodynamic parameters are updated at each step of the integration. A check is made at each step on the proximity of the saturation line, and two-phase flow is allowed. Turbulence is allowed in both the normal and the superfluid. Results are shown for conditions that may be typical for the transfer of large volumes of He II in space. The main result is that flow rates of 1000 liters/hour should be achievable with the receiver being 100% filled with saturated liquid He II.

INTRODUCTION

An important tool for analyzing superfluid helium transfer is a simplified physical model of the process. The model described here was developed by Ball Aerospace Systems Division, and applied to studying the replenishment of cryogen in the Space Infrared Telescope Facility (SIRTF) (ref. 1). It constitutes an extension of a previous model of forced He II flow (ref. 2). The intention of the model is to be physically rigorous by applying existing analytical knowledge of bulk superfluid helium behavior in such a way as to bound the characteristics of transfer between two dewars without addressing design details.

The previous He II bulk flow model (ref. 2) only analyzed subcooled transfer, using constant physical properties. A model was needed which applied continuous physical properties, and could deal with saturated liquid and boiling in order to accurately reflect the system behavior for this study. This extension of existing analytical techniques takes the form of a numerical model on the computer.

The first goal of the model was to check the feasibility of transfer at high flow rates. Since there exists some question as to the exact behavior of superfluid at the high Reynolds numbers encountered in this transfer study, the feasibility can be determined by quantifying the sensitivity of the process to the realistic bounds on the behavior of the fluid. That is, we compare the results using a model of a laminar superfluid flow, as is observed in counterflow experiments, to a model using the equations for fully developed turbulent flow of ordinary fluid.

The second goal of the model is to identify the He II transfer system design drivers. This is important to do before detailed design of transfer hardware is begun because the limits on realistic configurations are explored quantitatively and problem areas can be efficiently identified. As the detailed design progresses the model is modified and expanded and develops into a design optimization tool.

DESCRIPTION OF THE MODEL

The model consists of all the essential elements necessary for calculating the end-to-end equilibrium physical profile. The hardware elements modeled are shown in Figure 1. The flow proceeds from the supply dewar through the thermomechanical pump down the pipe and into the receiver dewar. Elements not modeled but examined were the effect of valves and pipe bends on the pressure drop, and the mechanism of the heat leak. The addition of these effects was determined not to significantly affect the results. The quantities needed to assess the performance of our configuration are calculated and displayed graphically. They are the temperature, pressure and heat conduction profiles of equilibrium steady state flow.

Two separate sets of equations are used in the model. The first set is the high thermal conductivity, laminar flow bound. The second set is the zero thermal conductivity, turbulent flow bound. Actual behavior will be between these limits.

The equations used for the laminar flow limit are shown in Table I (ref. 3). Equation (I-A) describes conservation of mass in the two fluid model where V_n is the normal component velocity and V_s is the superfluid component velocity. Equation (I-B) describes the laminar flow hydrodynamics of the normal component. Equation (I-C) describes the heat transfer of the fluid where the second term, the Gorter-Mellink mutual friction, dominates. Equation (I-D) describes conservation of energy where the normal component of the superfluid carries all the entropy. Equation (I-E) describes the heat conducted through the column of liquid (ref. 4).

The equations used for the turbulent flow limit are shown in Table II. Equation (II-A) describes the Blasius formulation of the turbulent flow pressure drop. Equation (II-B) describes the heat transfer for a non-conductive fluid.

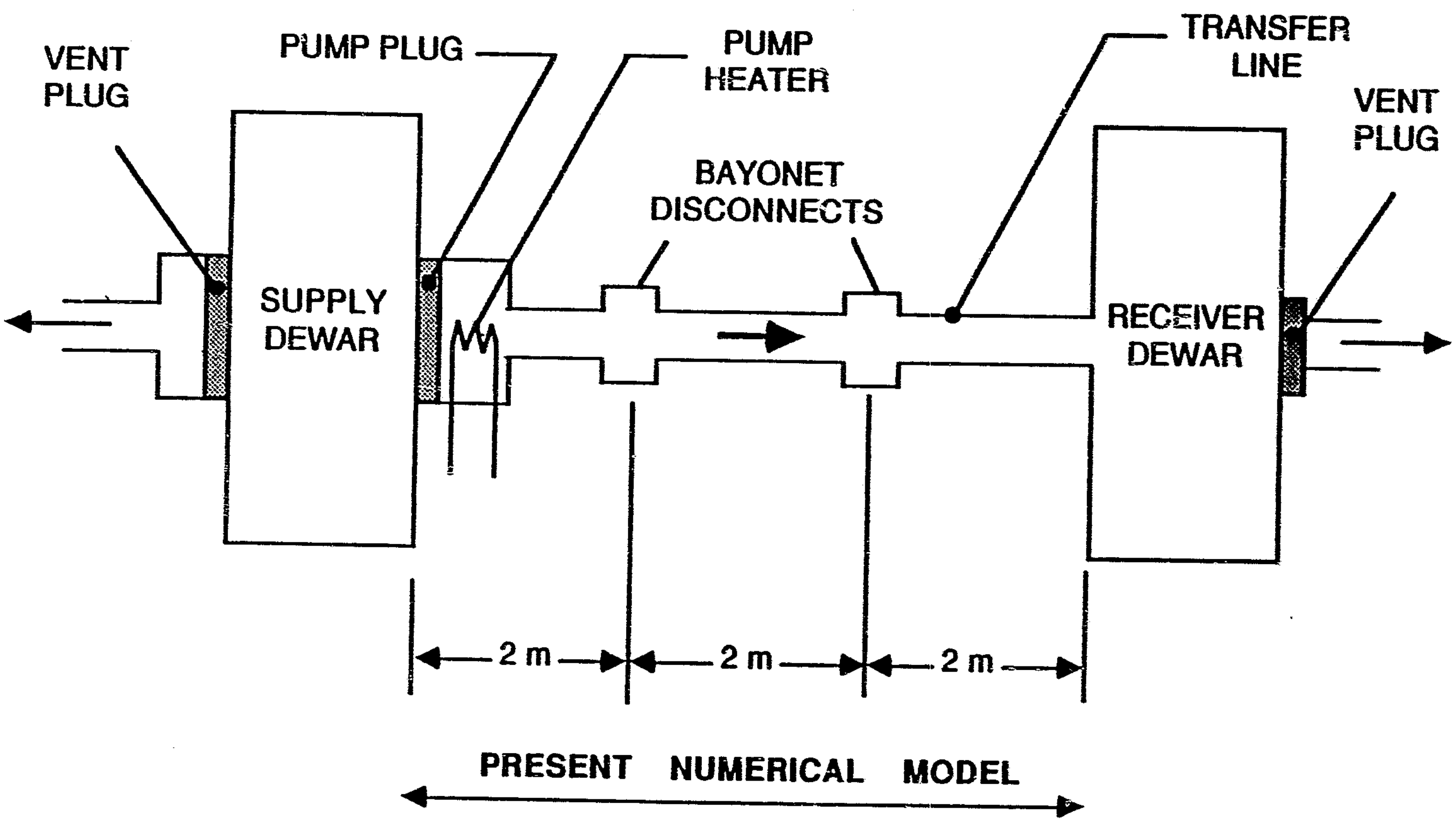

Figure 1 Hardware Configuration as Modeled

TABLE I - LAMINAR LIMIT EQUATIONS

η	=	viscosity	V_s	=	superfluid component velocity
$\dot{m}$	=	mass flow rate	A	=	crossectional area
ρ_n	=	normal component density	P	=	pressure
ρ_s	=	superfluid component density	l	=	line length
T	=	temperature	D	=	line diameter
S	=	entropy	ρ	=	total density
Q	=	heat leak into line	a	=	mutual friction coefficient
V_n	=	normal component velocity	q	=	heat conduction

(A) $$\frac{\dot{m}}{A} = \rho_n V_n + \rho_s V_s$$

(B) $$\frac{dP}{dl} = \frac{-32\eta\, V_n}{D^2}$$

(C) $$\frac{dT}{dl} = \frac{1}{\rho S}\frac{dP}{dl} + \frac{a\rho_n}{S}(V_s - V_n)^3$$

(D) $$\frac{d}{dl}(A\rho V_n ST) = \frac{dQ}{dl}$$

(E) $$q = A\rho_s ST\,(V_n - V_s)$$

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TABLE II - TURBULENT LIMIT EQUATIONS

P	=	pressure	$\dot{m}$	=	mass flow rate
l	=	line length	D	=	diameter
Q	=	heat leak	C_p	=	heat capacity
ρ	=	density	T	=	temperature
η	=	viscosity			

(A) $$\frac{dP}{dl} = \frac{-.2414\ \dot{m}^{4/7}\ \eta^{1/4}}{\rho\ D^{17/4}}$$

(B) $$\frac{dQ}{dl} = \dot{m}\ Cp\ \frac{dT}{dl}$$

In order to observe liquid-gas transitions anywhere in the line, it was necessary to create a numerical computer model which uses continuous physical properties. The technique selected for solving the equations was a finite difference method where the simultaneous non-linear differential equations are solved iteratively. Initial values, based on the conditions of the supply dewar and the London equation for the thermomechanical pump, are propagated in 1 cm increments downstream to the line/receiver dewar interface. Successive runs are made shooting for the equilibrium receiver Dewar boundary condition, which for our configuration is saturated liquid in the receiver, and zero heat conduction between the line output and receiver dewar. These equilibrium conditions were determined on the basis of the restoring forces which come into play. That is, if the receiver condition predicted by the equations is too warm or too cold, heat will be conducted out of or into the receiver resulting in a equilibrium temperature either lower or higher. Also, if a condition is calculated where the liquid becomes saturated and some of it boils before reaching the receiver, then the pressure drop in the line becomes greater. For this case more pumping force would be required so the actual equilibrium flow rate would be lower.

The equations and the physical model are incorporated into a previously-developed modeling code, called SLIM (System Level Interactive Model). SLIM provides the code required for easy parameter input and output, selection of initial conditions, profile graphing and documentation.

RESULTS

The model was run for a supply dewar and thermomechanical pump operating at 1.8 K. The temperature, conduction, and integrated heatleak profiles for the laminar flow limit are shown in Figure 2. The turbulent flow limit profile is shown compared to the laminar limit for the same operating conditions in Figure 3. The equilibrium receiver dewar conditions for these cases are given in Table III. Temperature profiles (Figure 4) were calculated for three different line diameters representing three widely different Reynolds numbers.

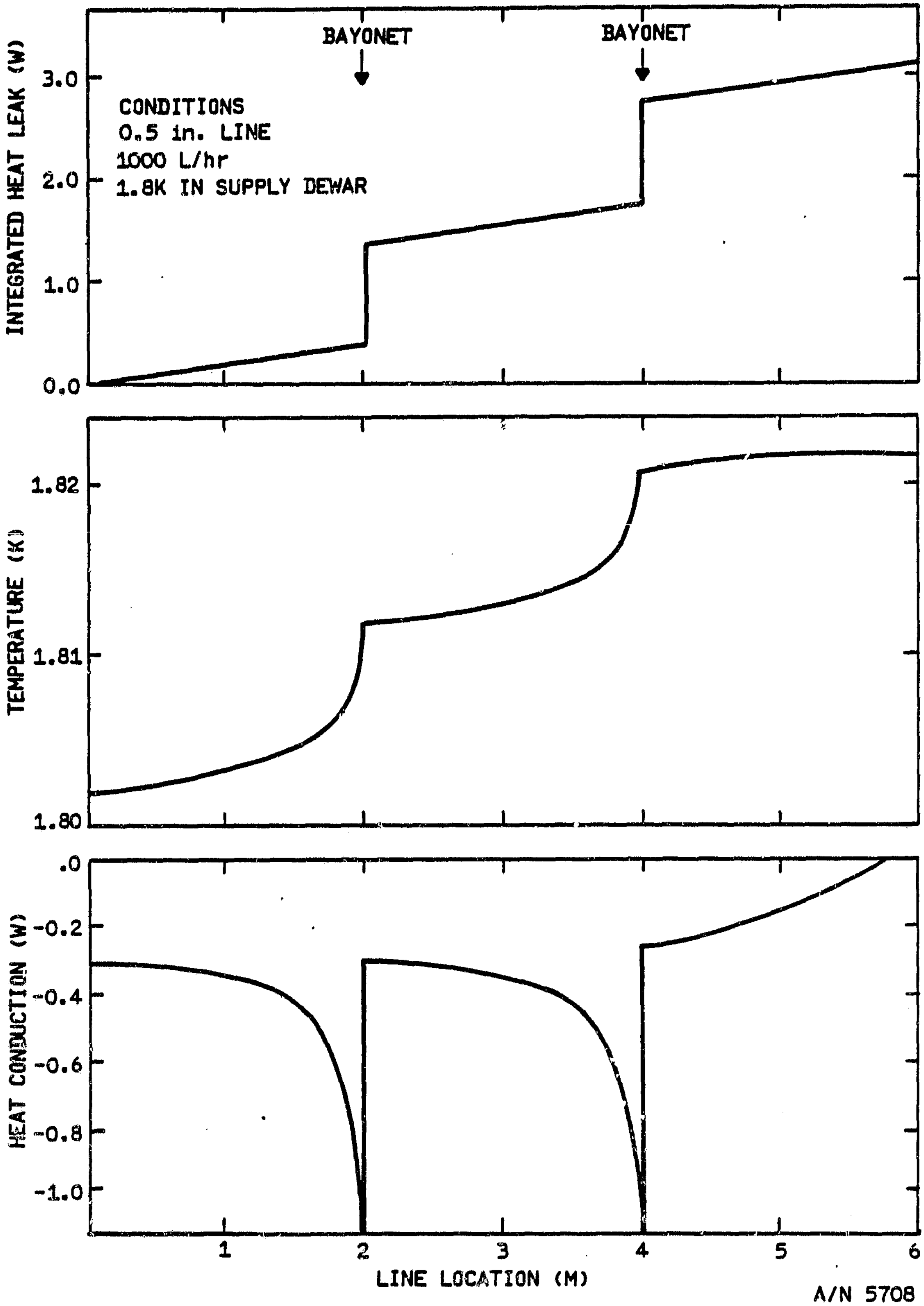

Figure 2 Heat Flow Along Transfer Line for Laminar Superfluid Flow

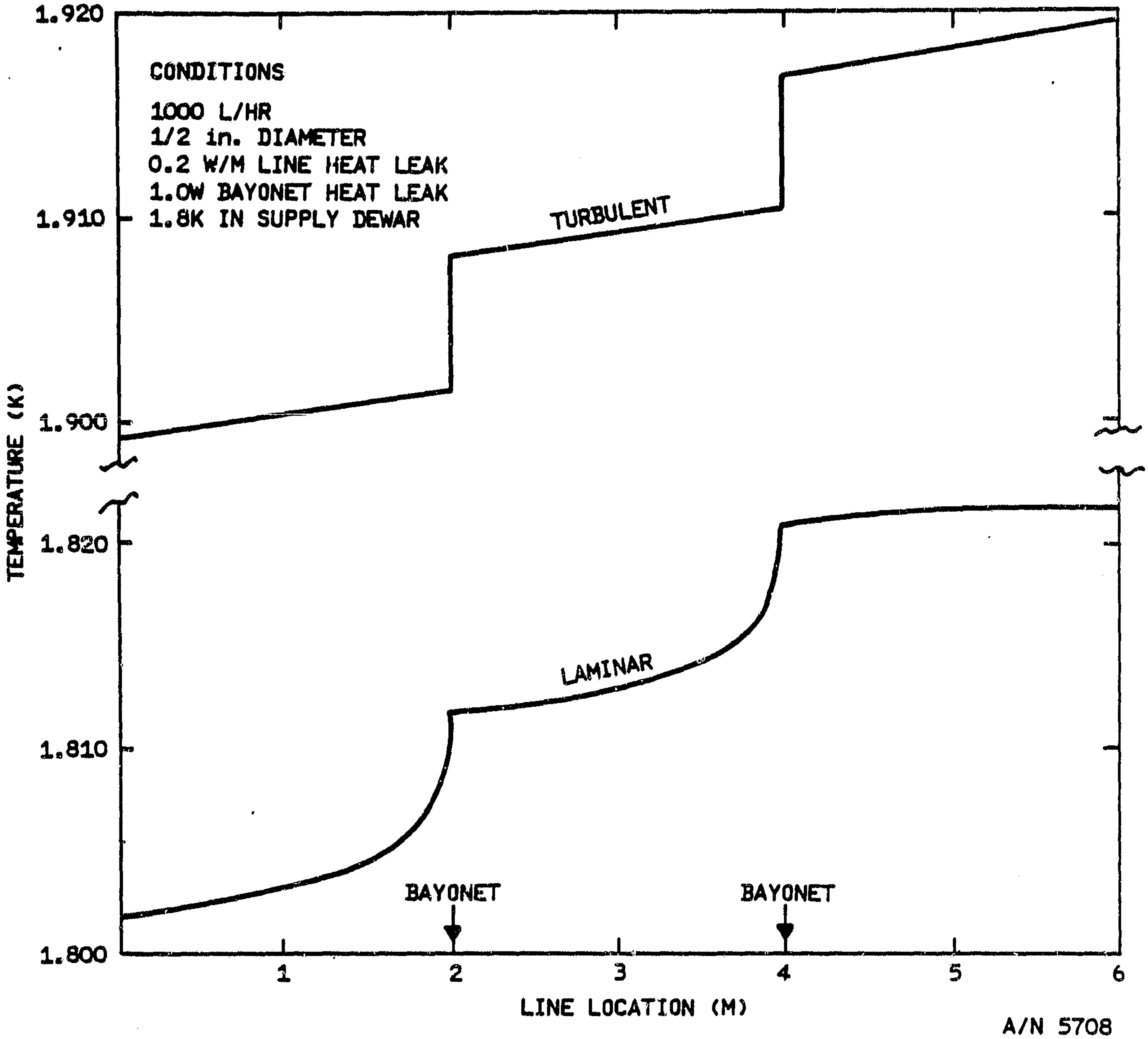

Figure 3 Temperature Along Transfer Line for Laminar and Turbulent Flow Limiting Conditions

TABLE III - EFFECT OF FLOW REGIME

CONDITIONS MODELED	
Line Diameter	1/2 in
Line Length	6 M
Flow Rate	1000 L/hr
Supply Dewar Temperature	1.8 K
Two Bayonets Heat Leak	1 W each
Line Heat Leak	0.2 W/M

RESULTS

	Laminar Flow	Turbulent Flow
Plug Heater Power	39.1897 W	55.109 W
ΔT across Pump Plug	0.00177 K	0.0992 K
ΔP across Pump Plug	1.042 torr	58.40 torr
Line ΔP	0.0365 torr	52.312 torr
SIRTF Temperature	1.8216 K	1.9194 K

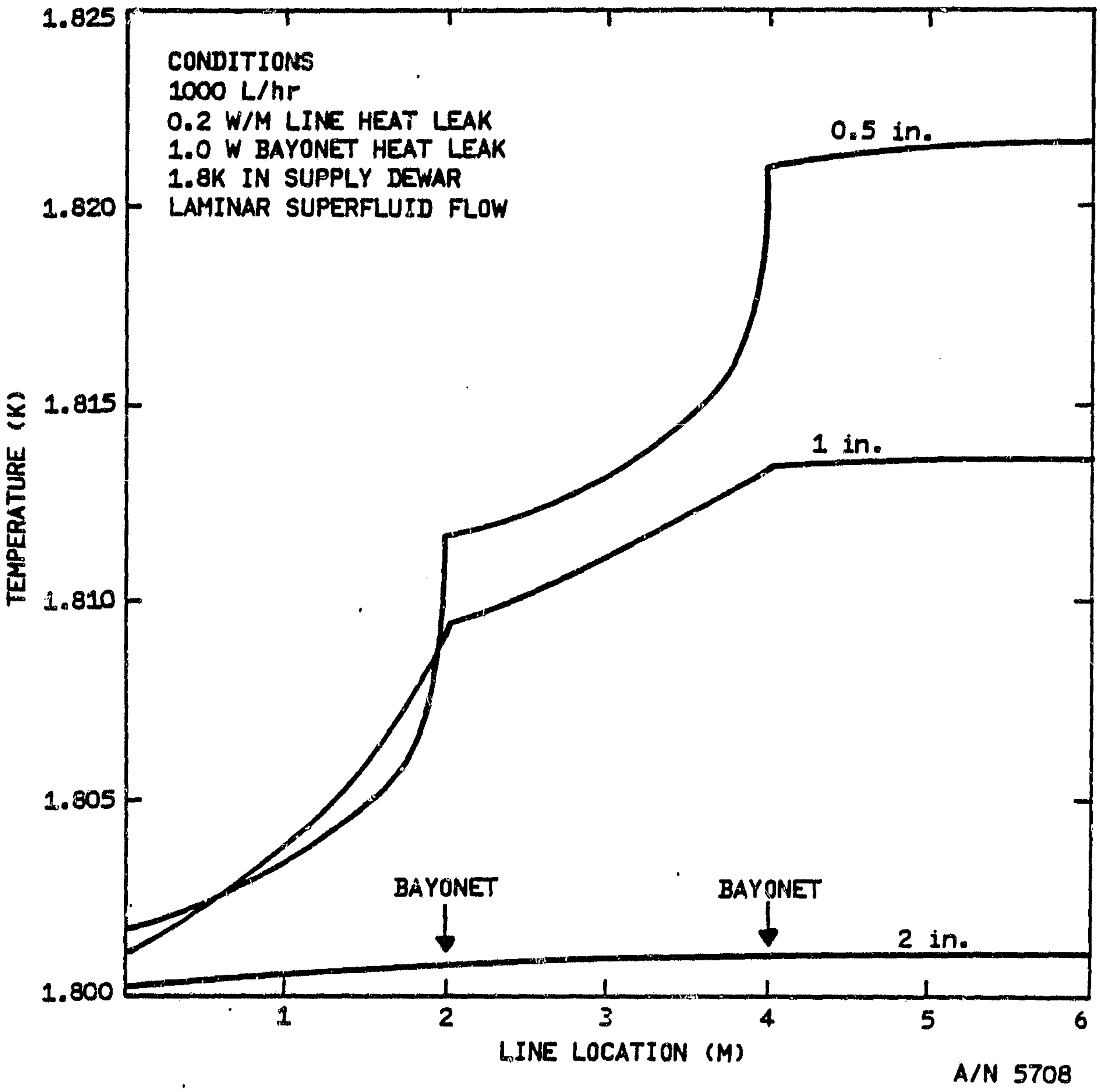

Figure 4 Effect of Line Diameter on Temperature

A comparison of transfer operating temperatures of 1.6 K and 1.8 K are made in Table IV in the turbulent flow limit. Either operating temperature results in a reasonable pressure drop and less than 0.1 degree Kelvin rise in temperature between supply and receiver. The heater power required for transfer at 1.8 K is much greater than at 1.6 K since the zero entropy fluid coming out of the pump must be raised to a higher temperature, but the overall behavior remains the same.

For laminar flow of the superfluid the energy from the heater and heatleaks goes into raising the flow rate and the temperature of the receiver. Table V and Figure 4 show that for higher Reynolds numbers, caused by smaller pipe diameter, not only is the pressure drop increased but less heat is conducted back to the plug; thus more heater power is required to maintain the flow and more of the heatleak goes into raising the temperature of the fluid. Increased pressure drop and lower heat conduction result in a higher receiver temperature.

The most notable effect of line diameter for our application is that the shape of the laminar flow temperature profile approaches that of the turbulent flow limit when the bulk fluid velocity is high, i.e., high Reynolds numbers. That is, the conduction of heatleaks through the fluid becomes negligible as is the case for ordinary fluid. In all cases it is important to note that the line pressure drop for laminar flow increases for high fluid velocities but remains very small. The pressure drop is no problem even when very high Reynolds numbers are modeled using the turbulent flow equations. The results in Table III show receiver conditions (1.92K saturated liquid) which are still reasonable for our application. Thus the pressure drop and the heat transfer mechanism do not seem to be design drivers since the flow will take place with just slightly different conditions at the receiver.

TABLE IV - EFFECT OF TEMPERATURE

CONDITIONS MODELED

Line Diameter	1 in.
Line Length	6 M
Flow Rate	1000 L/hr
Turbulent Flow	
Two Bayonets Heat Leak	1 W each
Line Heat Leak	0.2 W/M

RESULTS

	SUPPLY DEWAR TEMPERATURE	
	1.6 K	1.8 K
Plug Heater Power	19.341	40.492
ΔT across Pump Plug	0.0129	0.0071 K
ΔP across Pump Plug	3.993	4.1789 torr
Line ΔP	2.427	2.664 torr
SIRTF Temperature	1.6581	1.833 K

TABLE V - EFFECT OF LINE DIAMETER

CONDITIONS MODELED	
Line Diameter	1/2 in.
Line Length	6 M
Flow Rate	1000 L/hr
LAMINAR Flow	
Two Bayonets Heat Leak	1 W each
Line Heat Leak	0.2 W/M

RESULTS

	TRANSFER LINE SIZE		
	1/2 in.	1 in.	2 in.
Plug Heater Power	39.1897 W	37.975 W	36.20 W
ΔT across Pump Plug	0.00177 K	0.0011 K	0.0002 K
ΔP across Pump Plug	1.042 torr	0.64757 torr	0.11774 torr
Line ΔP	0.0365 torr	0.00223 torr	0.0001355 torr
SIRTF Temperature	1.8216 K	1.81342 K	1.800975 K
Heatleak Conducted to Plug	0.3 W	1.42 W	3.07 W

CONCLUSIONS

The analysis performed with this model shows that the thermomechanical transfer method will work regardless of the particular conductive attributes of the superfluid. The transfer will result in the receiver being 100% filled with saturated liquid. Also this analysis shows that flow rates of 1000 liters/hour should be achievable. The feasibility of superfluid pumped transfer is not dependent on the exact behavior of He II at high Reynolds numbers. Assuming the Gorter-Mellink formulation as the high thermal conductivity bound and ordinary turbulent fluid mechanics for the non-conductive bound, the existence or not of some type of turbulent He II is not a driver for the SIRTF replenishment application.

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APPENDIX C

HELIUM-I TO HELIUM-II CONVERSION EQUATION AND THERMODYNAMICS

The following is the derivation of the thermodynamic equation used for calculating the mass fraction of liquid helium lost during cooldown. The cooldown is accomplished by venting the saturated liquid to a lower pressure, thereby producing a lower temperature.

First of all, the work done on the fluid is given by

$$dW = - P\, dV, \tag{C-1}$$

where P is the pressure and V is the volume. Secondly, the heat leaving the liquid and being delivered to the surface layer for evaporation is given by

$$dQ = l\, dm, \tag{C-2}$$

where l is the latent heat of vaporization per unit mass and m is the mass of the liquid. Finally, the change in the internal energy of the fluid is given by

$$dU = dQ + dW. \tag{C-3}$$

Combining equations 1 through 3, we get

$$l\, dm = dU + PdV. \tag{C-4}$$

Since (dU + PdV) is the change in total enthalpy of the fluid, equation (4) can be written as

$$l\, dm = dh\, m, \tag{C-5}$$

where h is the enthalpy per unit mass of the fluid.

Since we are looking for the ratio of the final mass of fluid to the initial mass, we must solve equation (C-5) for m_f/m_i. First we get

$$\int_{m_i}^{m_f} \frac{dm}{m} = \int_{T_i}^{T_f} \frac{dh}{l} \tag{C-6}$$

The right hand side of equation (C-6) can be integrated analytically by approximating l as a constant over the temperature interval. Thus,

$$\ln m_f - \ln m_i = \frac{h(T_f) - h(T_i)}{l_{average}} = \frac{\Delta h}{l_{average}} \tag{C-7}$$

and

$$\frac{m_f}{m_i} = \exp\left(\frac{\Delta h}{l_{average}}\right) \tag{C-8}$$

For Figure 2-4 the right hand side of Equation (C-6) was integrated numerically using continuous helium properties.

Appendix D
CRYOGENIC ANALYSIS

This appendix contains analysis backing up certain conclusions stated in Section 2 of the report. The topics covered are:

1) Sensitivity Evaluation of SIRTF Cooldown Cycle
2) Estimate of ASE Dewar Size to Resupply SIRTF
3) Cooldown GHe Conduction Analysis
4) Estimate of Contact Conductance Across Thermal Joints for SIRTF
5) Cooldown Limiting Factors
6) Heat Transfer Coefficient and Resulting Conductance in Single Tube Heat Exchanger Loop for SIRTF Cooldown

Sensitivity Evaluation of SIRTF Cooldown Cycle

The following analysis develops thermal conductance coefficients which represent the IRAS cooldown performance. These coefficients are then modified to represent COBE and SIRTF configurations and cooldown predictions made. The COBE predictions for quantity of cryogen required were within 4% and the cooldown time prediction was conservative by 30%. Based on the analysis, 4772 liters are required to cool the SIRTF system from 300K to 2K, and the cooldown can be achieved in 29 hours: if the fill line is wrapped around the tank; if adequate thermal joints are provided to the instruments and telescope; and if the vent line is 2.5 cm in diameter.

The analysis of a dewar "cool down" is very difficult if a pure analytic approach is taken. For the most part this is caused by the modeling uncertainties. If a Thermal Math Model is made to agree with known cooldown data then that model can be used to extrapolate results for other configurations. This approach was taken to predict COBE cooldown (with fairly good results) based on IRAS experience. With this methodology proven, SIRTF was modelled. The main "actor" was identified for the SIRTF cooldown, and typical temperature responses are included in this analysis. In addition, it was discovered that throttling the LHe supply could save as much as 30% of the supplied helium with no increase in cooldown time.

The basic model is composed of four nodes:

NODE #	NODE
998	Helium supply at 2K
3	Gas in the cryogen tank
2	Tank
1	Mirror (Telescope)

and three conductors:

CONDUCTOR #	FROM	TO
20	Helium supply (998)	gas (3)
11	gas (3)	tank (2)
10	tank (2)	mirror (1)

The thermal capacitance of the tank and the mirror for the three difference dewars are based on the following weights and materials:

WEIGHT (Kg) - MATERIAL

NODE	IRAS	COBE	SIRTF
MIRROR (1)	72Kg Beryllium	181Kg Aluminum	422Kg Aluminum
TANK (2)	105Kg Aluminum	120Kg Aluminum	670Kg Aluminum

Conductor G(20) is the fill rate conductor. The helium fill rate for IRAS and COBE was modelled as 50 l/hr. The fill rate for SIRTF was assumed to be 200 L/hr.

Conductor G(11) is the gaseous conduction term. It is a strong function of temperature and was calculated for IRAS to be;

(T(2)+T(3))/2 K	G(11) mW/K
10	1640
20	3410
50	5780
150	13240
250	18440
300	18440

G(11) for COBE was assumed to be 1.28 times the IRAS value. G(11) for SIRTF was assumed to be 5.28 times the IRAS value. This is strictly based upon the surface area ratios of the tanks.

G(10) is the conduction across flexures from the tank to the mirror. The value of this path was based partially on Jerry Siebert's work on low temperature interfaces and partially on tailoring the shape of the G(10) vs Temperature curve so as to match IRAS. The value of G(10) for SIRTF is quite a bit larger and is based on the fact that this joint is to be enhanced by means of thermal straps. While the magnitude is much larger, compared to IRAS data, the shape was kept the same. See Figure 1.

Figure 1 Comparison of IRAS and SIRTF Optic System Thermal Conductance

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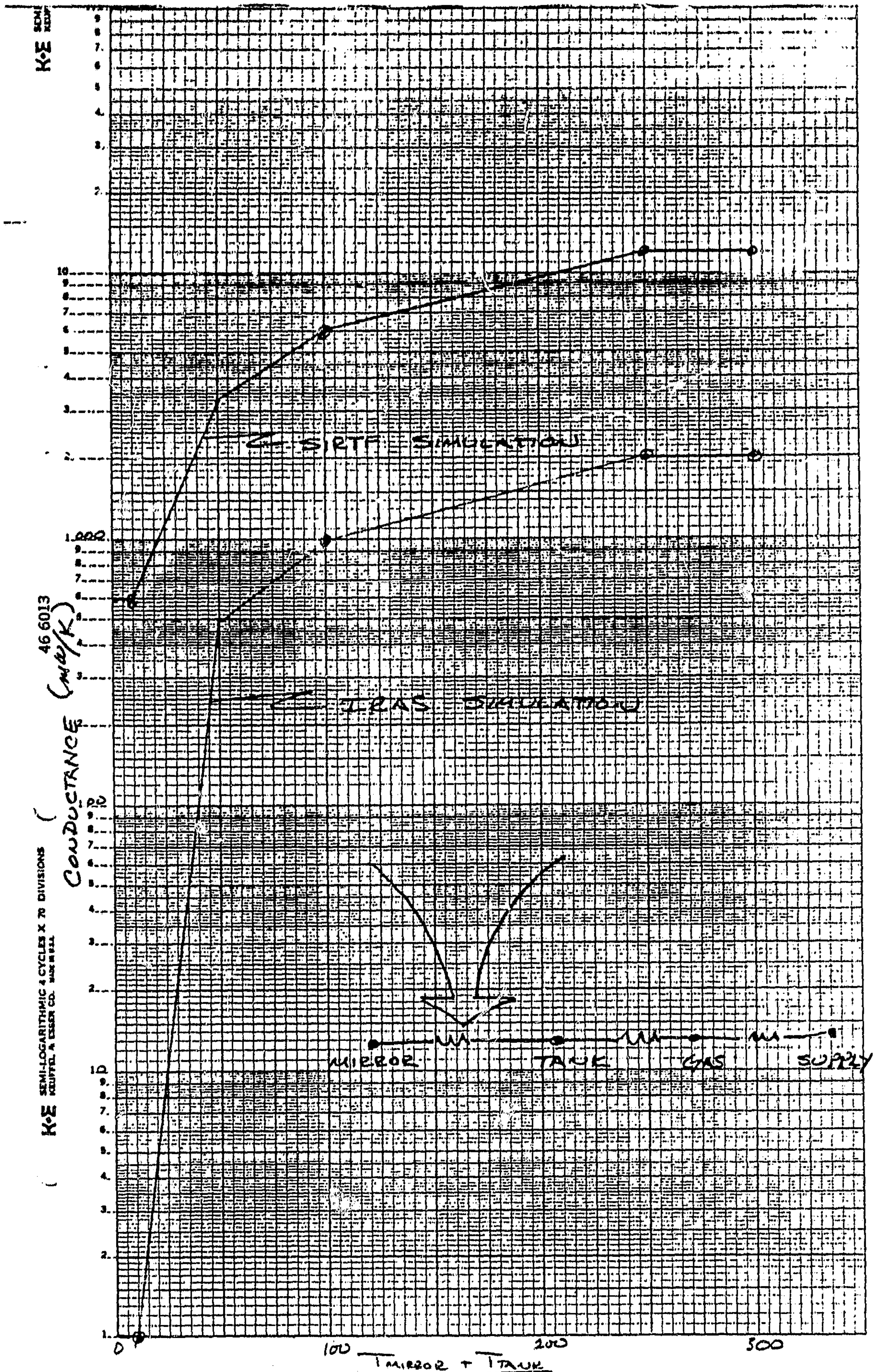


C-4

Figure 2 is the IRAS simulation and compares favorably with data found in IRAS log books.

Figure 3 is the COBE simulation for a flexure conductance G(10) the same as IRAS.

Figure 4 is the COBE simulation for a flexure conductance G(10) the same as SIRTF.

Figure 5 is the SIRTF simulation which shows that for the nominal configuration approximately 45 hours will be needed for a cooldown from 300K.

Figure 6 is for SIRTF with the flexure conductance G(10) twice its nominal value. This leads to a 30% saving in cooldown time.

Figure 7 is for SIRTF with the gaseous conduction term G(11) doubled. This provides a marginal improvement of about three hours.

Figures 8 and 9 are the same types of SIRTF data but from an initial temperature of 150K.

Figures 10, 11, and 12 indicate that considerable savings in the amount of helium needed to cool down can be had by throttling the supply. This can be achieved with no loss of time which indicates that the flexure conductance is dominant and a wide open supply valve only helps in the beginning of the cooldown.

Figure 13 is a plot of the gaseous conduction G(11) term independently arrived at by Doug Regenbrecht. This value is somewhat higher than was nominally used, but shows a response in Figure 14 very similar to the nominal SIRTF prediction in Figure 5.

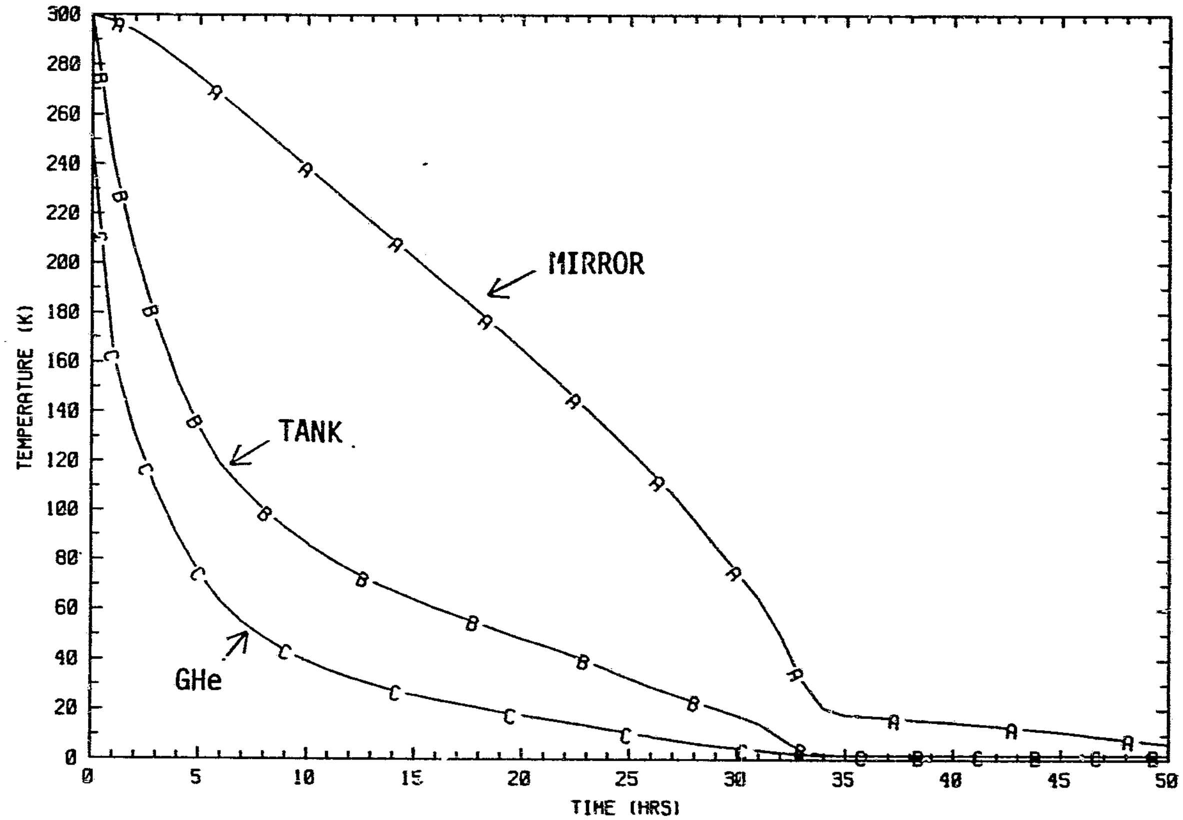


Figure 2 IRAS Cooldown Simulation

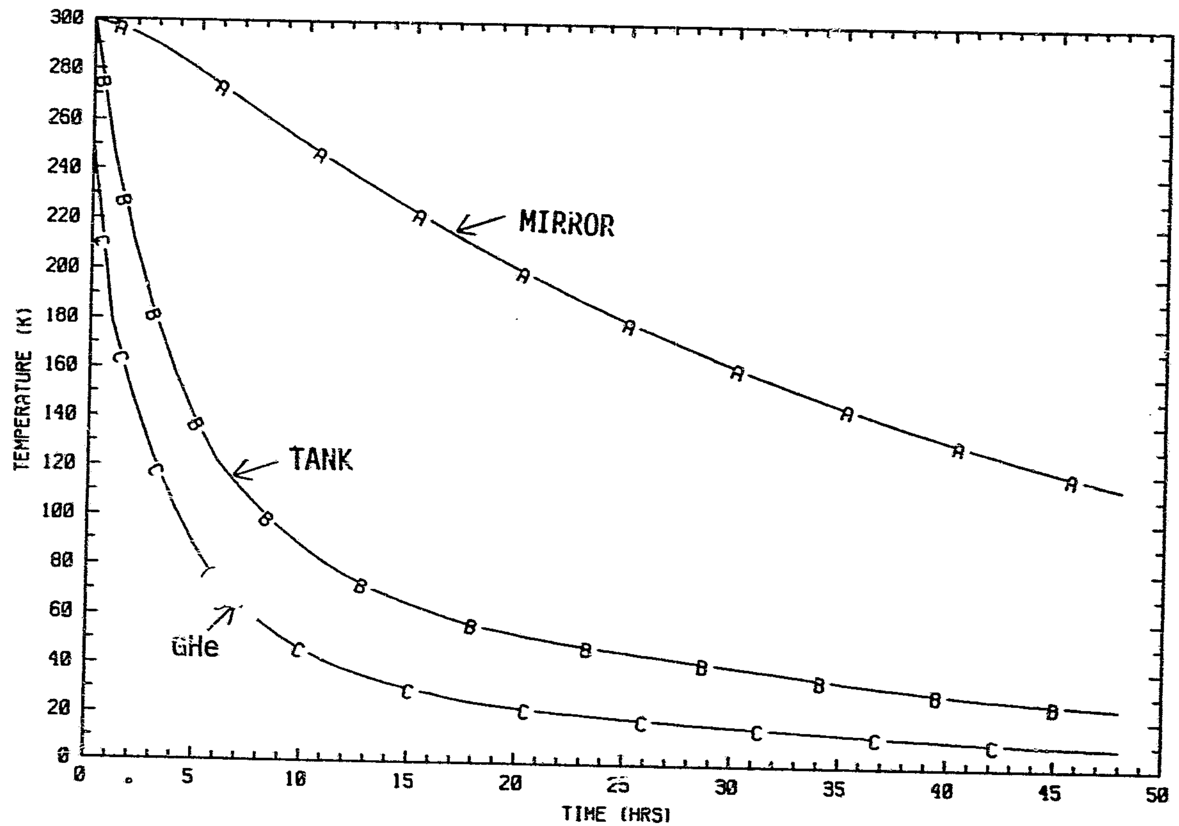


Figure 3 COBE...IRAS-Like Conductance G(10)

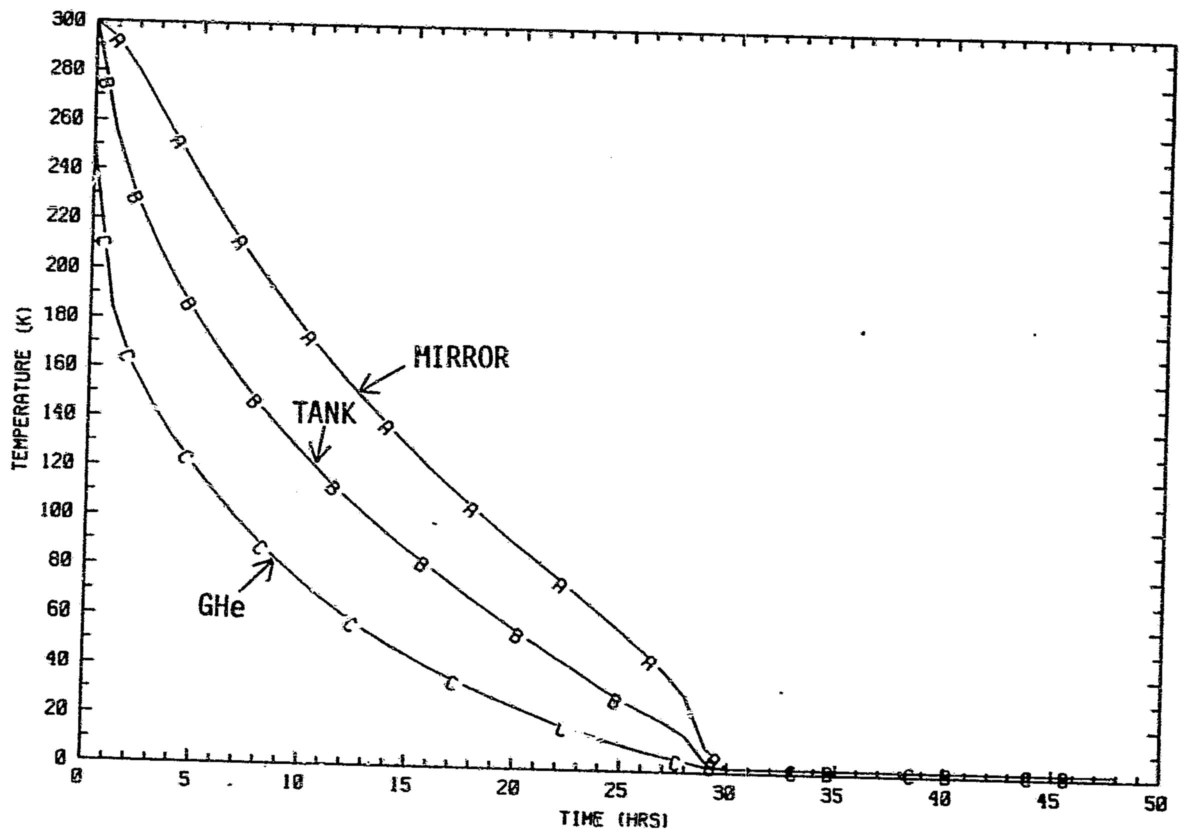


Figure 4 COBE...SIRTF-Like Conductance G(10)

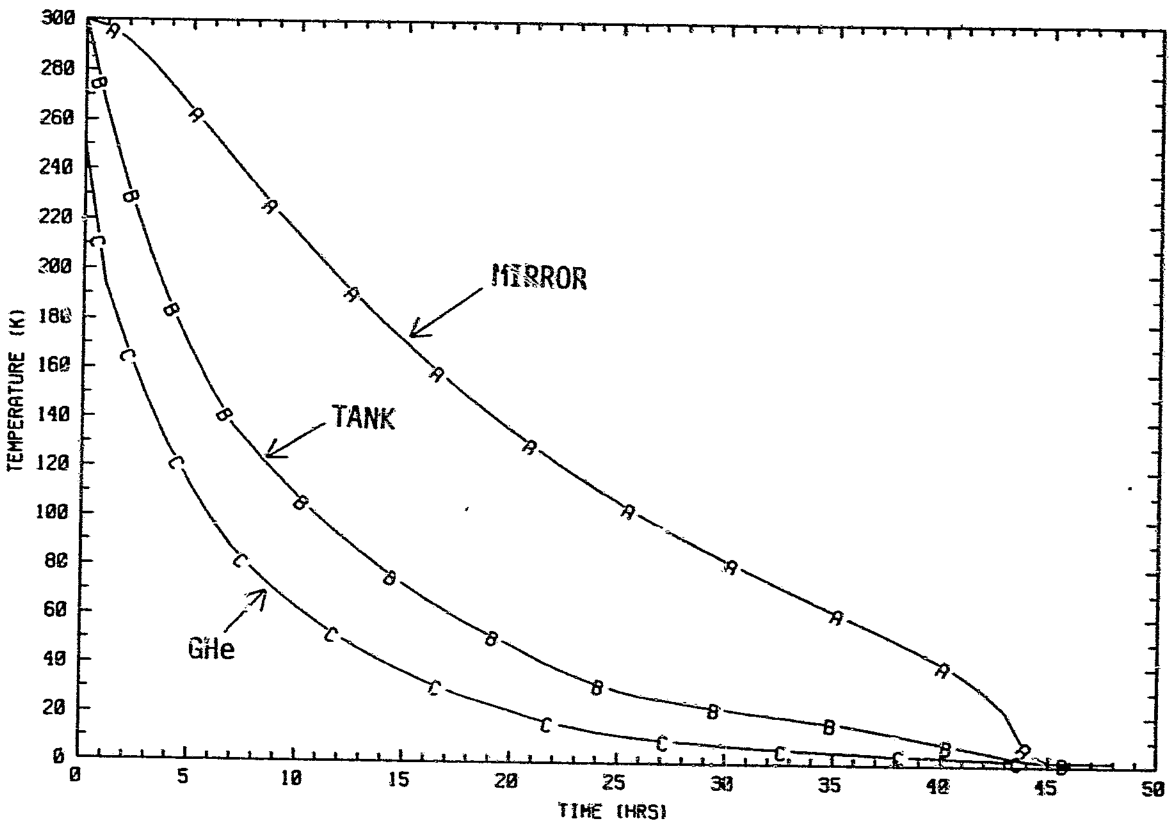


Figure 5 SIRTF (Baseline) Flow=200L/Hr.

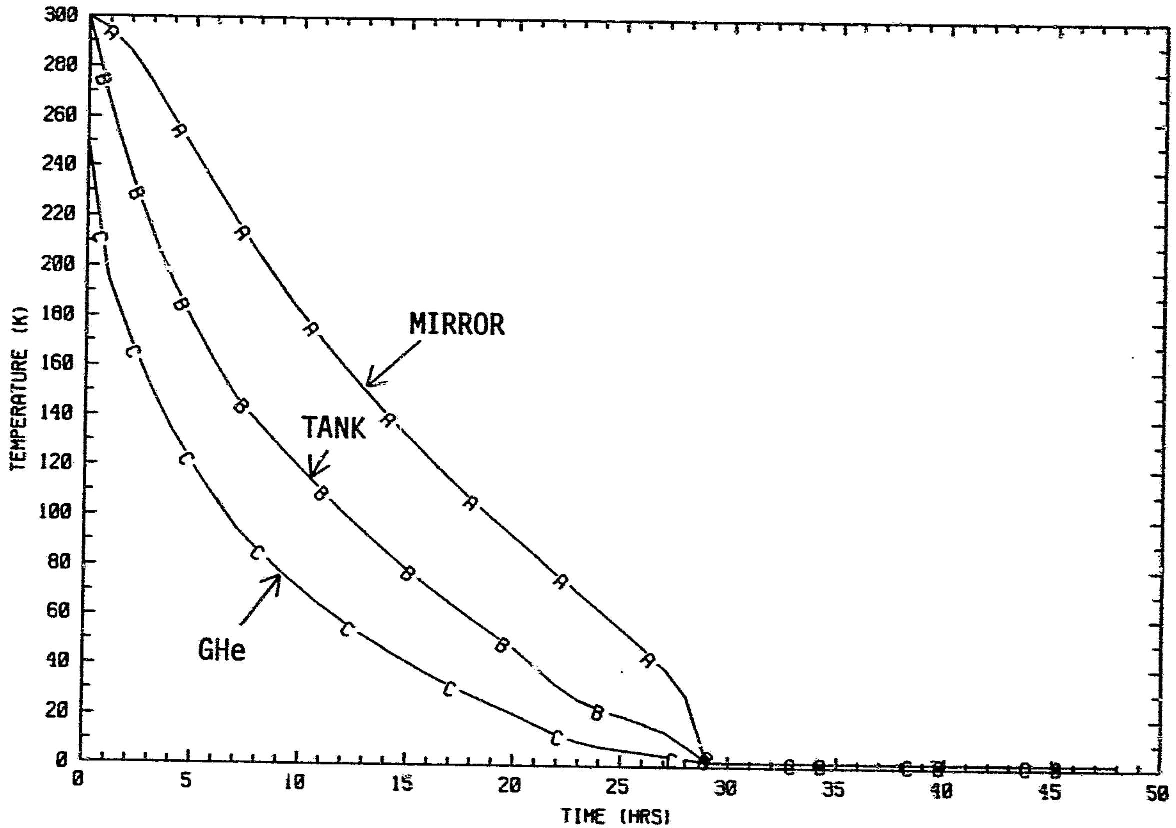


Figure 6 SIRTF...GFLEY-GFLEX*2 G(10)

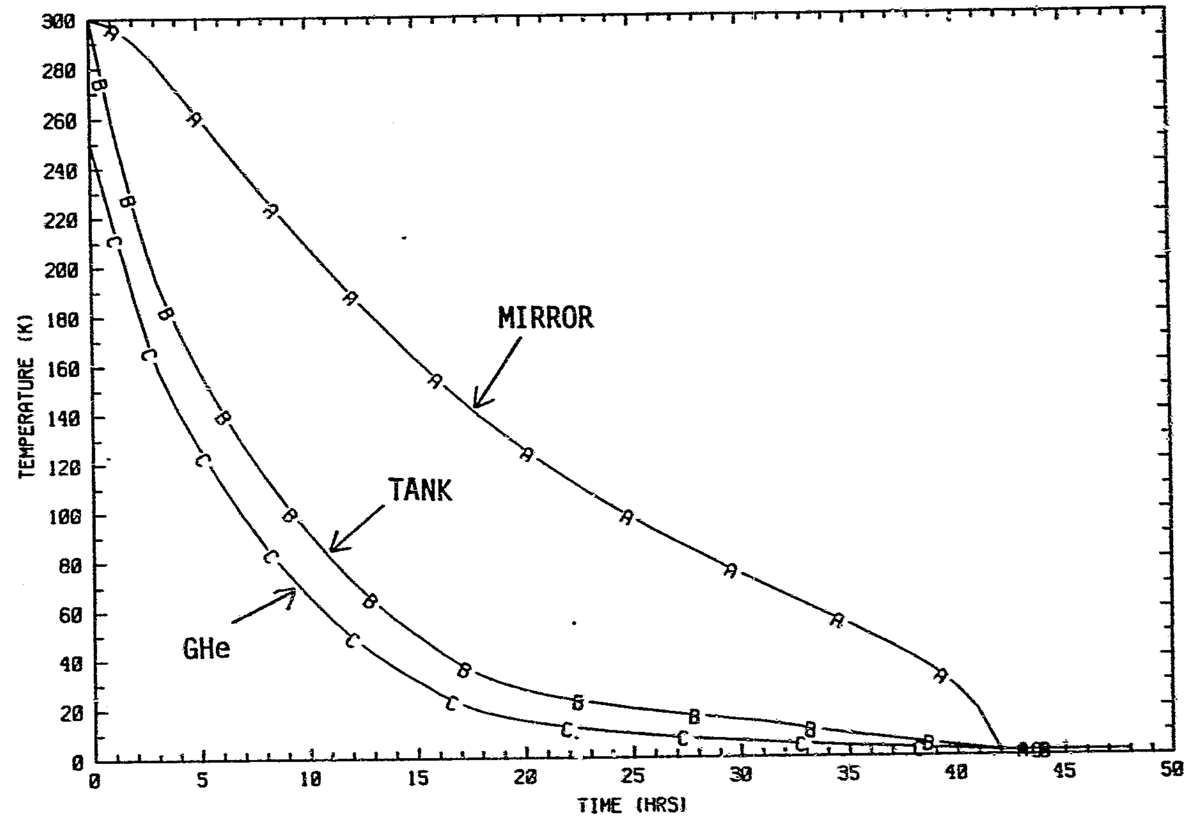


Figure 7 SIRTF...GCONV=GCONV*2. G(11)

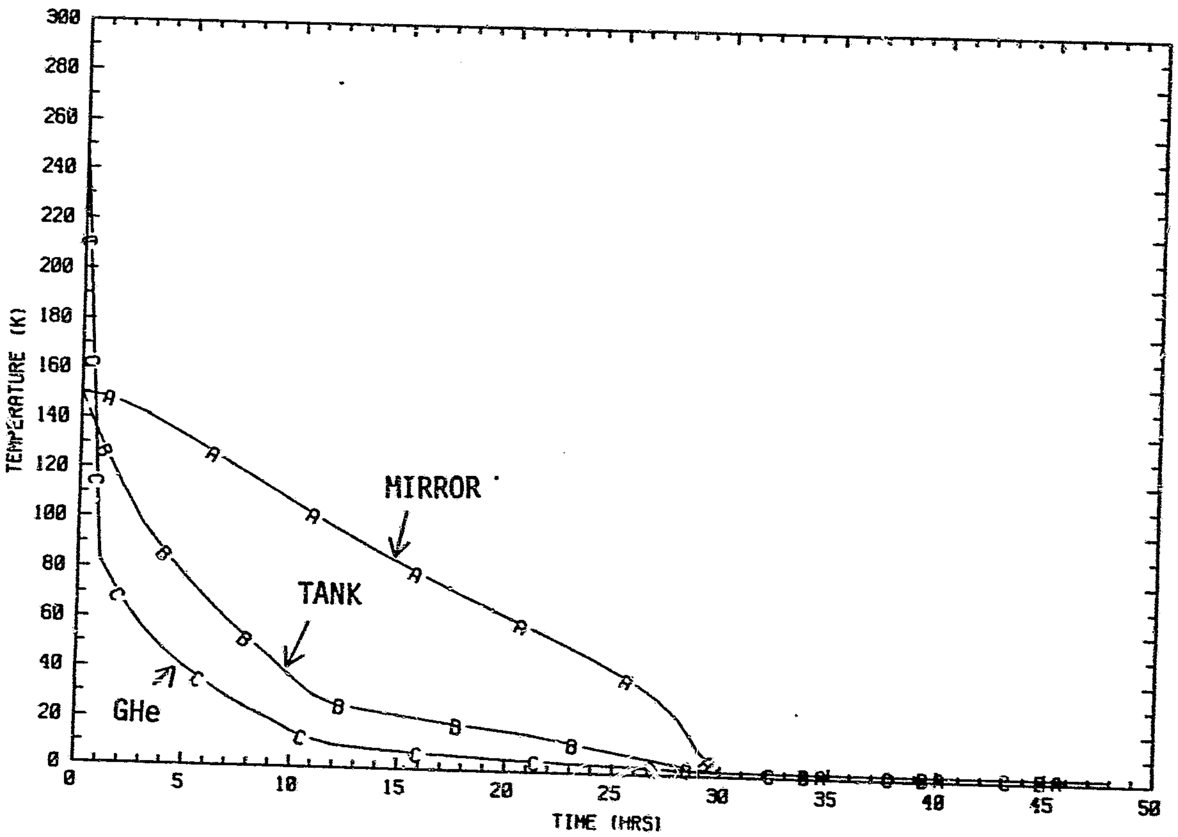


Figure 8 SIRTF Baseline - 150k Starting Temperature

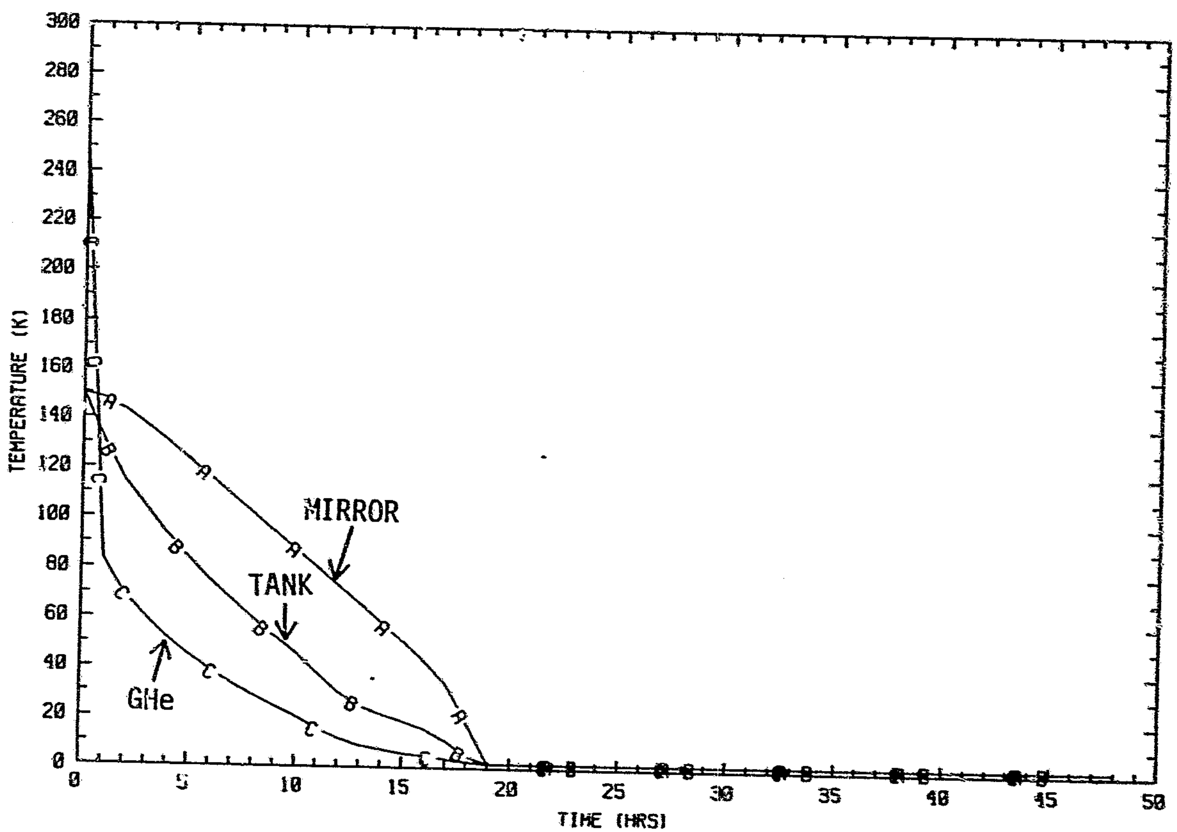


Figure 9   GFLEX=GFLEX*2. (SIRTF-150K Starting Temperature)

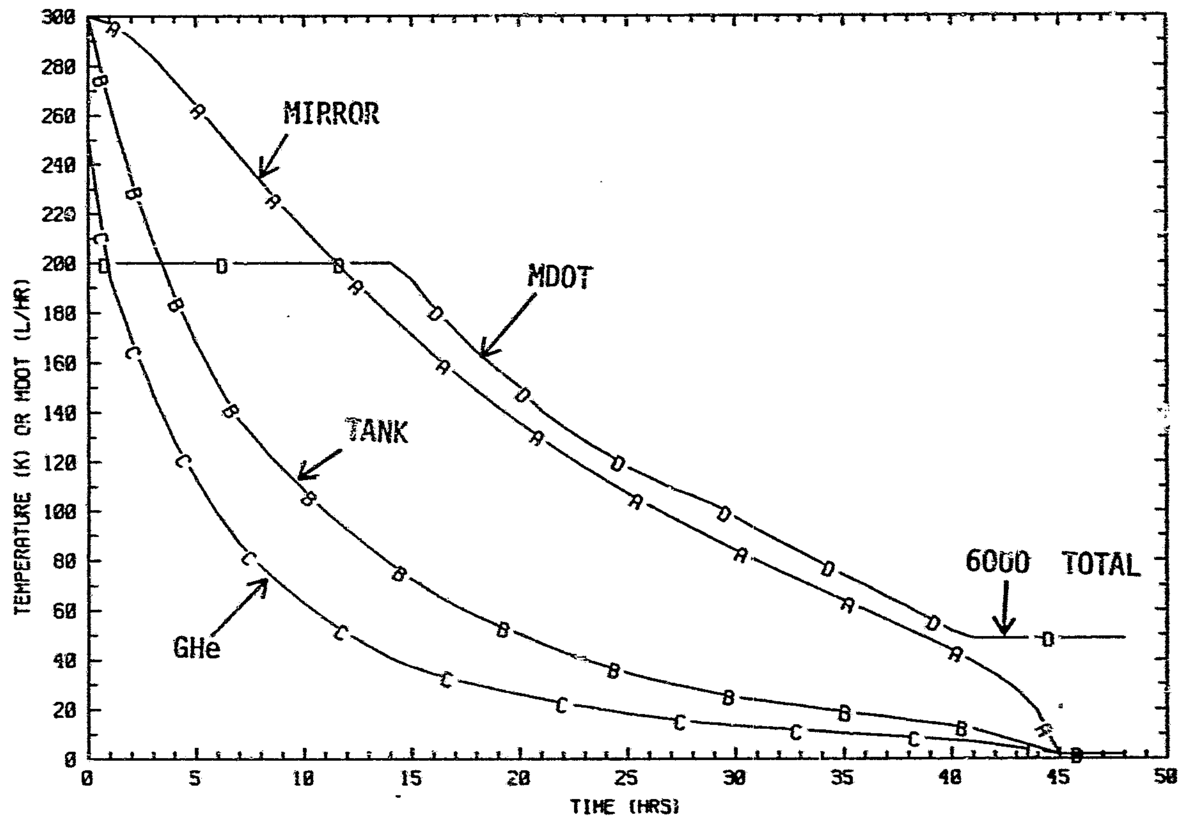


Figure 10 SIRTF Baseline w/Flowrate

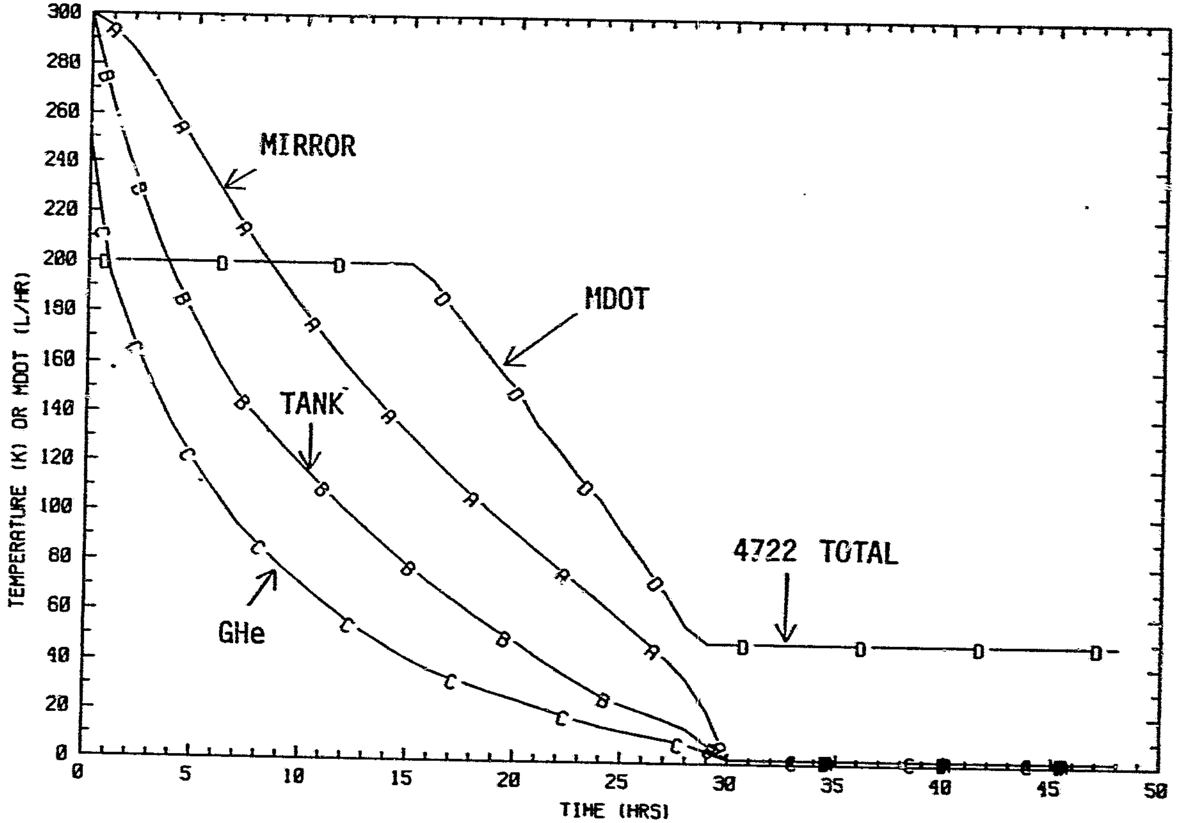


Figure 11 SIRTF w/G10-G10*2.

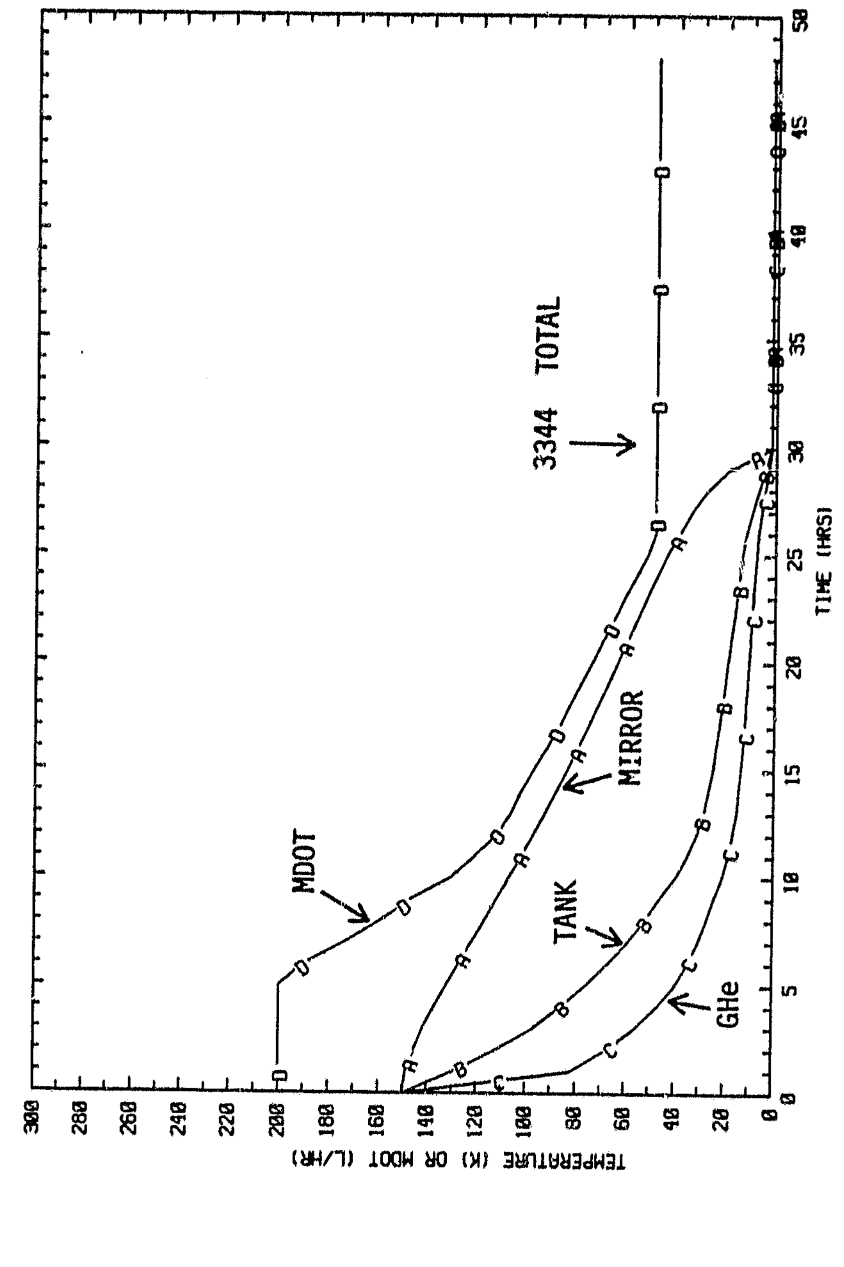


Figure 12 SIRTF w/T(Time=0)=150K

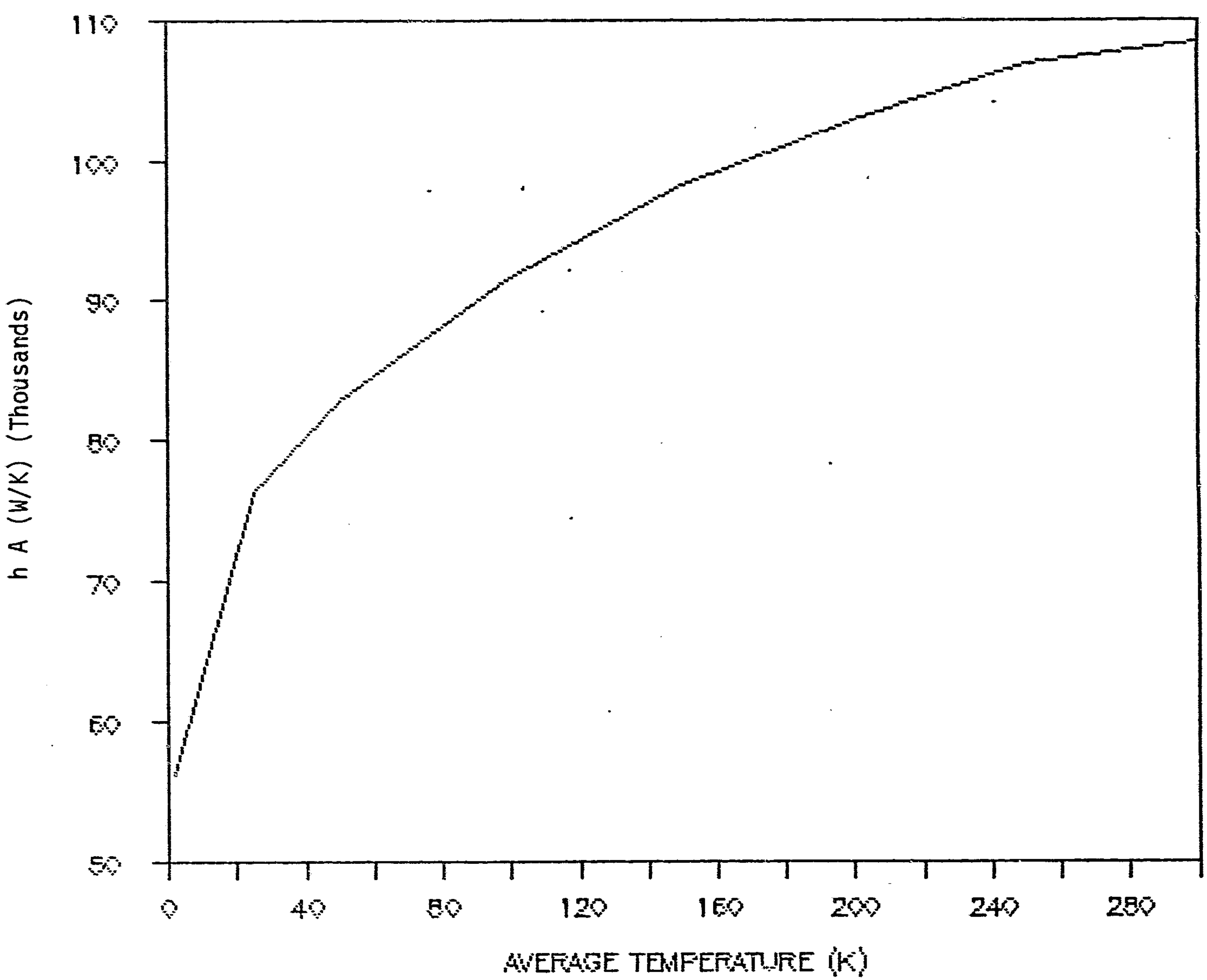


Figure 13 Gaseous Helium Conductance with Heat Exchanger

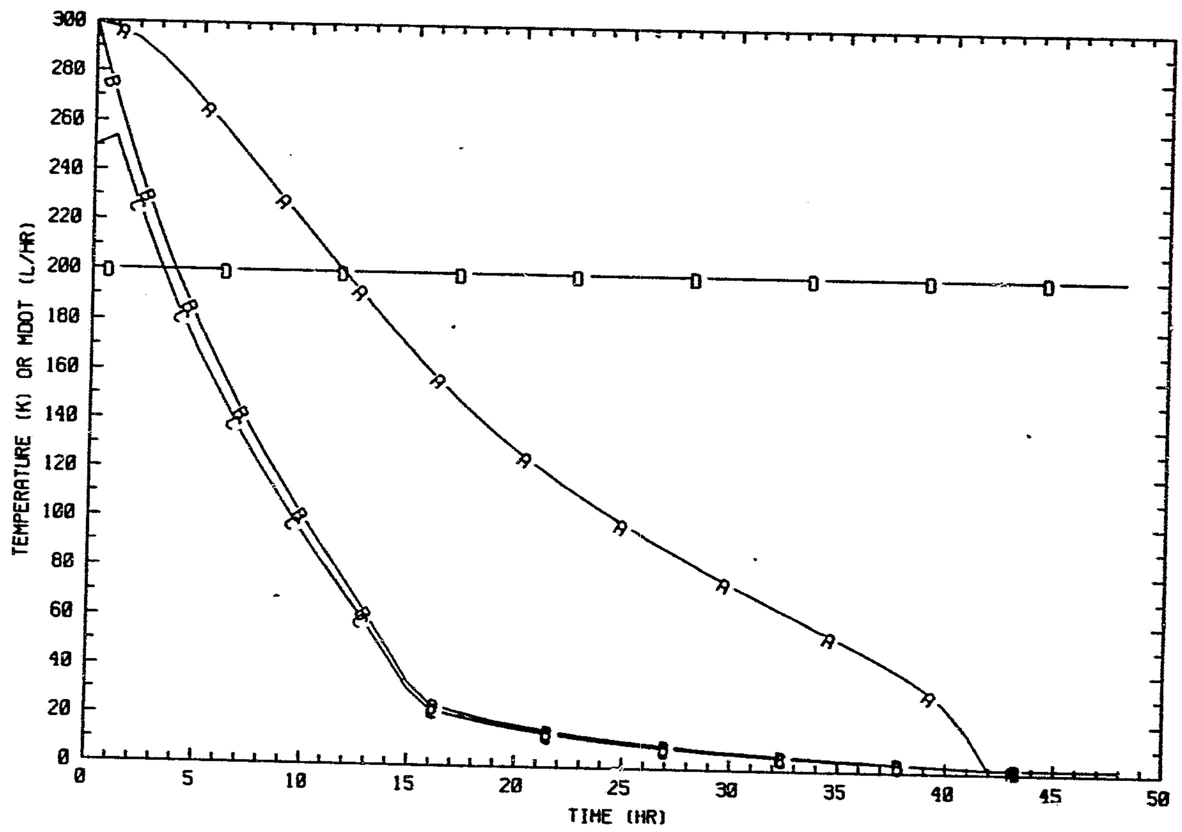


Figure 14 Convection Data Using a Heat Exchanger

Estimate of ASE Dewar Size to Resupply SIRTF

This analysis presents the evaluations made to determine the quantity of SfHe required to fill the SIRTF satellite on orbit.

Parameters considered in this analysis include:

- Quantity of cryogen required to cool system
  - -Transfer efficiencies
  - -Margins
  - -Affect of supply dewar thermal performance on cryogen quantity
  - -SIRTF temperature
  - -Hold time

This analysis also utilizes the results of other analysis performed regarding the STICCRS study such as thermal joint contact resistance, methods for improving the GHe cooldown transfer rate, and the results of a transient thermal model of the SIRTF, COBE, and IRAS dewars.

The results of this sizing effort is that for a 0.1% per day loss rate supply dewar; 5300 liters of superfluid helium are required to fill a cold <10K SIRTF; 9800 liters are required to cool and fill a SIRTF that is initially at 150K as might be the case if SIRTF ran out of cryogen and was left in its orbit for a long period of time; and 11,750 liters are required to cooldown and fill SIRTF from 300K as might be the case if an instrument changeout was performed.

Estimate of ASE Dewar Size to Resupply SIRTF

Tasks to be performed and documented in this analysis include:

1. Receiver tank temperature effect on quantity of cryogen required.
   Evaluate: A receiver tank with a temperature less than 10K, 150K, and 300K.

2. Evaluate effect of Supply dewar performance on quantity of cryogen required. Consider 0.5%, 0.2%, and 0.1% loss rates per day. 0.5% is equivalent to a commercial supply dewar, 0.2% is equivalent to the IRAS insulation system performance with a cylindrical vessel, and 0.1% is an IRAS system with a fourth vapor cooled shield.

3. Miscellaneous parameters to be assumed include-

   - Hold time of 90 days, i.e., 60 days hold time with a 50% margin.

   - Transfer efficiency of 95%, that is the topoff value achieved on IRAS. Analysis for STICCRS of an all SfHe transfer would indicate that a value of 95-98% efficiency can be achieved.

I. <u>Quantity of LHe required to precool the received tank and transfer line system.</u>

Assume transfer line is 2.5 centimeters dia. x 0.04 cm wall thickness and 3 meters long.

Q to be removed -

$2.5\ (\pi)\ .04\ (300) = 94.2\ \text{cm}^3$

ρ of CRES $= 0.3\#/\text{in}^3 = 0.3\ (453)/16.4\ \text{cm}^3$

$= 8.3\ \text{gm/cm}^3$

$M = 8.3\ (94.2) = 781.2\ \text{gm}$

ΔH_{CRES} 300K to 2K = 81.1 Joules/gm

Q to be removed = 781.2 gm (81.1 Joules/gm)
= 6.34×10^4 Joules

Qty of LHe required to precool transfer line assy

ΔH of LHE = 20.3 Joules/gm

Qty = $6.34 \times 10^4/20.3$ = 3121 gms

ρ_{LHe} = 0.125 gm/cm^3

Qty LHe = 25 liters

Case 1.

Qty of LHe Req'd to Fill a Wet >10K 4000 Liter Receiver Tank.

Assume 95% eff. - 4000 = 4210 liters

Add 15% margin = 632 liters

Compare 0.5%, 0.2% and 0.1% per day loss rates for dewar size.

0.5%/day loss

For 4840 liters - 8450 liters

0.2%/day loss - 5900 liters

0.1%/day loss - 5300 liters

Case 2. Qty of LHe Req'd to fill a Cryogen tank at 150K

Cooldown qty for Cryogen tank, MIPS, and Telescope = 3344 liters based on IRAS and COBE tank configuration GHe conductances per SER ARU-004 combined with a metal to metal conductance of 1200 mW @ 2K, 6000 mW 2-20K, and 24,000 mW @ 20K and above.

Reference SER ARU-003

Qty of LHe Reqd.

Precool of transfer line -		25 liters
Precool of Receiver Tank 95%		3520 liters
Fill tank 95% eff.		4210 liters
Margin 15%		1163 liters
TOTAL		8918 liters

Hold time of 90 days

		SUPPLY DEWAR SIZE
0.1%/day	-	9800 liters
0.2%/day	-	10870 liters
0.5%/day	-	16120 liters

Case 3. Qty of LHe Req'd to Fill a Cryogen Tank @ 300K.

Cooldown quantity for Cryogen tank, MIPS, and Telescope = 4772 liters based on IRAS and COBE. Performances and an analytical prediction for SIRTF as documented in SER TKK-03.

Qty of LHe Reqd.

Precool Transfer Line	-	25 liters
Precool of Receiver Tank	-	5053 liters
Fill Tank	-	4210 liters
Margin 15%	-	1325 liters
TOTAL	-	10,681 liters

Hold Time of 90 days

		SUPPLY DEWAR SIZE
0.1% day	-	11,750 liters
0.2% day	-	13,000 liters
0.5% day	-	19,500 liters

Lifetime that a 11,750 liter dewar will provide using a 0.1%/day loss rate.

Quantity required after hold time = 4867 liters.

Quantity available for on-orbit hold = 11,750 - 4867 = 6883.

Loss per day = 11.75 liters

Hold time = <u>585 days</u>

<u>Hold time for a Wet/Cold cryogen tank to fill a 120 liter dewar.</u>

Quantity required =

Transfer line cooldown	-	25 liters
Transfer efficiency	-	6 liters
Margin	-	15 liters
Fill	-	120 liters
TOTAL		166 liters

Quantity available - 11,750 liters

Hold time quantity - 11,584 liters

11,584/11.75 liters/day loss rate = 985 days hold time

Size of supply dewar to service a 10,000 liter receiver dewar which is @ 2K temperature.

Transfer line cooldown	-	100 liters
Transfer Eff. 95%	-	500 liters
Margin	-	1500 liters
Fill	-	10,000 liters
TOTAL	-	12,100 liters

90 day hold time @ 0.1%/day loss rate

Hold quantity	=	1195
Total Quantity Reqd	=	13,295 liters

Quantity of LHe req'd to fill a storage dewar on Space Station 4867 liters req'd after 90 days = 5300 liters req'd

Precool supply dewar - 5053 liters

5300 (.15*) = 795 liters

Total Reqd = 11,148 liters plus ground hold of 30 days = 334 liters

Total = 11,482 liters

Cooldown GHe Conduction Analysis

This section presents an analysis of estimated GHe conduction coefficients experienced in the IRAS satellite cooldown and fill operations.

The results are:

18.44 w/K @ 250K
13.24 w/K @ 150K
5.78 w/K @ 50K
3.41 w/K @ 20K
1.64 w/K @ 10K

Cooldown of the IRAS cryogenic dewar system was accomplished by flowing LHe into a transfer line connected to IRAS. The liquid was vaporized and routed through the dewar fill line into the cryogen tank and then vented out the vent line. Connected to the cryogen tank was the optical telescope and experiment. On the inside of the cryogen tank are stiffener flanges 1.5 inches long so the flow was as pictured in Figure 1. As the transfer line, plumbing and cryogen tank cooled down the liquid helium interface gradually progressed to the tank and it eventually collected LHe and filled. This analysis documents the anticipated GHe conduction which can be expected using this type of cooldown procedure.

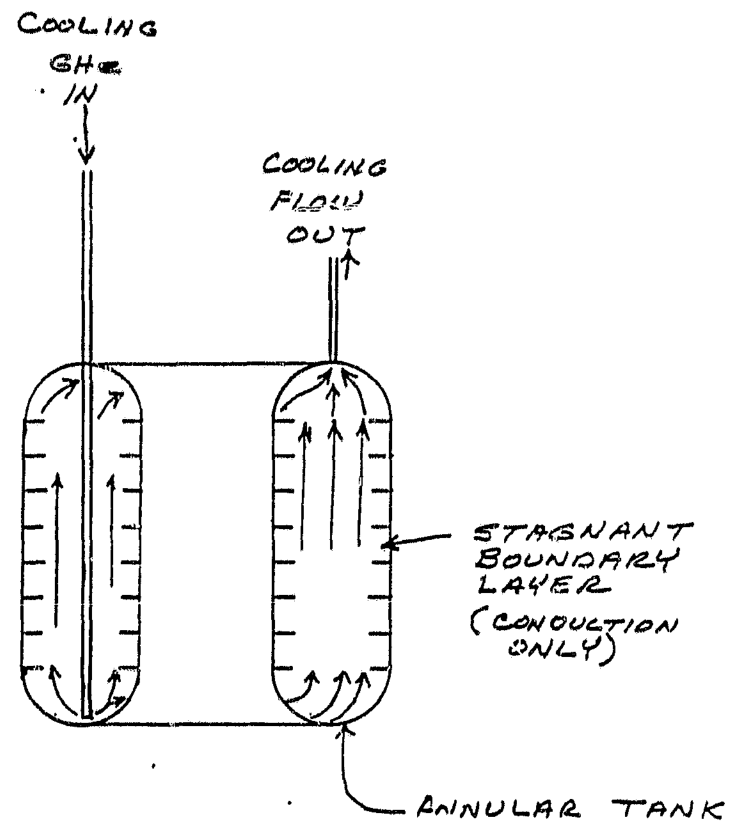


Figure 1.
IRAS Cryogen Tank Cooling Flow Pattern

Tank Inner Dia	-	32.20 in.
Tank Outer Dia	-	47.85 in.
Length	-	35.38 in.
Fin length	-	1.5 in.
Open Area	-	606 in^2 = 4.21 ft^2

Velocity of GHe assuming 50L/hr flowrate of Lite Q

300K	-	40,984 L/HR of GHe = 344.0 ft/hr
200K	-	25,646 L/HR of GHe = 215.0 ft/hr
100K	-	12,833.7 L/HR of GHe = 108.0 ft/hr
50K	-	6,420 L/GHe of GHe = 53.9 ft/hr
10K	-	1,250 L/GHe of GHe = 10.5 ft/hr

Assumptions - 1.0 atm. press

50 L/HR of LHe = 6.25 Kg/Hr flow

= 1250 Liters/Hr of GHe @ 10K

Velocity thru vent line -

Assume 0.47 I.D. = 0.0012 ft^2

vel @ 10K = 36,808 ft/hr = 613 ft/sec

vel @ 300K = 1.2×10^6 ft/hr = 20,185 ft/sec

Sonic vel. = 3,346 ft/sec

Flow @ room temp (300K) limited to 7L/hr

200K - 11.2 L/hr

100K - 22.4 L/hr

50K - 44.7 L/hr

Gaseous Conduction of Helium

1.35 mW/cmK @ 250K

0.97 mW/cmK @ 150K

0.47 mW/cmK @ 50K

0.25 mW/cmK @ 20K

0.12 mW/cmK @ 10K

Fin length = 1.5 inches = 3.8 cm

Surface Area of Tank ID = 32 in OD = 48 in

$$A = 32\ (\pi)\ 32 \text{ in } (2.54)^2 + 48\ (\pi)\ 32\ (2.54)^2 = 20{,}755 + 31{,}132 = 51{,}887 \text{ cm}^2$$

$$Q = \frac{KADT}{L} = \frac{1.35\ (51{,}887)\ 50K}{3.8}$$

=	922 watts @ 250K	=	18.44 W/K
=	0.97 (683) = 662 watts @ 150K	=	13.24 W/K
=	0.47 (615) = 289 watts @ 50K	=	5.78 W/K
=	$0.25 \frac{(51887)15}{3.8(1000)}$ = 51.2 watts @ 20K	=	3.41 W/K
=	$0.12 \frac{(51887)5}{3.8(1000)}$ = 8.2 watts @ 10K	=	1.64 W/K

IRAS EVALUATION

Specific Heat of Helium @

250K = 5.2 Joules/gmK
150K = 5.2 Joules/gmK
50K = 5.2 Joules/gmK
20K = 5.2 Joules/gmK
10K = 5.5 Joules/gmK

Max flow @ 250K (from page 2 = 9 L/hr)

Cooling power available = 5.2 Joules/gm -K (1125 gm/hr)50K
= 292,500 Joules/hr
= 2.9×10^5 Joules/hr

Qty of heat to be removed to cool IRAS dewar and telescope to 250K
45.4 Joules/gm (105,000) = 4.77×10^6
Mirror-Be Joules/gm (72,000) = 6.3×10^6
= 11.07×10^6 Joules
= 38 hours to cool?

Boundary layer cooling = 922 watts
= 3.32×10^6 Joules/hr

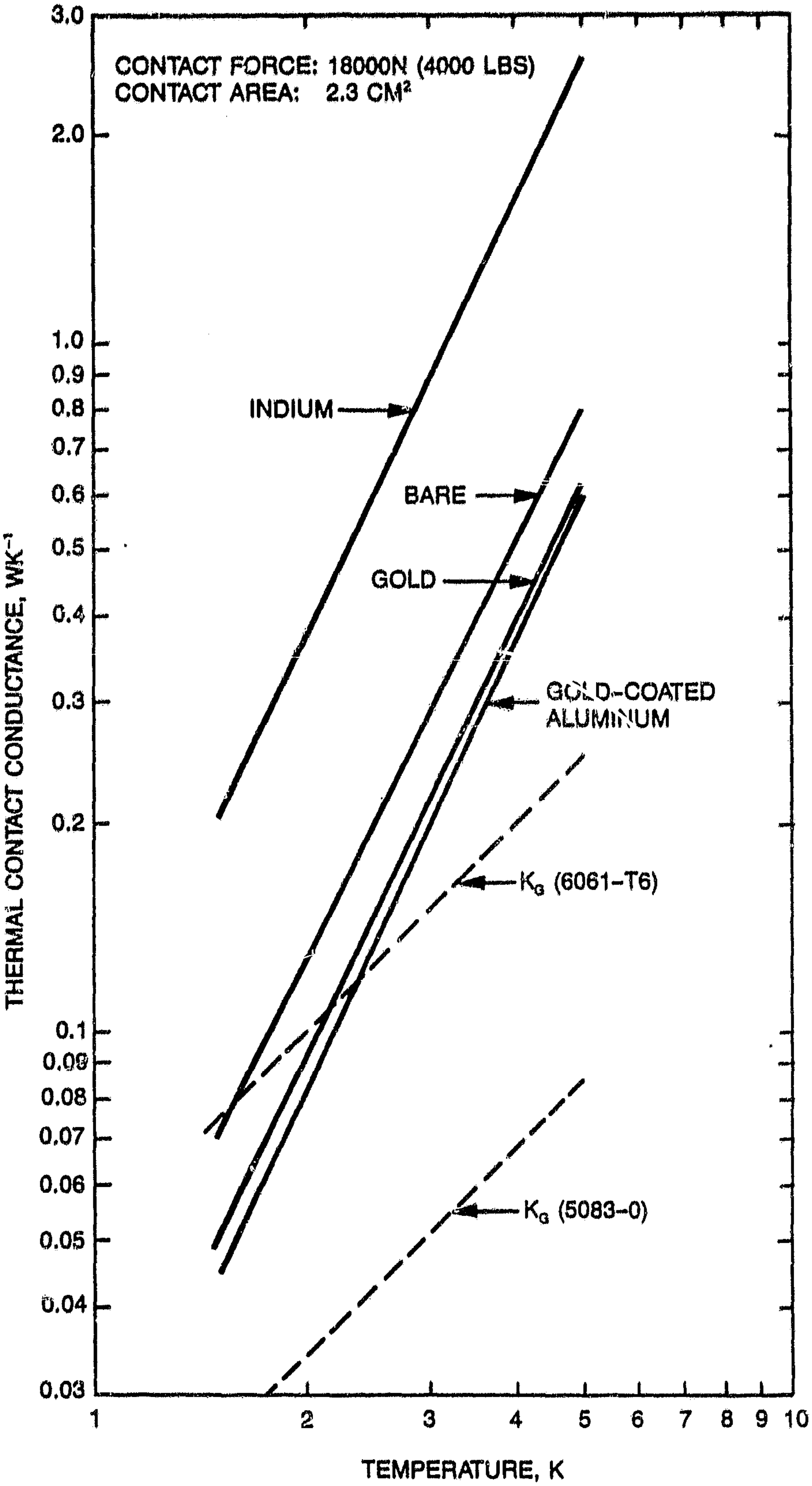
If we assume boundary layer controls cooldown rate time = 3.33 hours to cool to 250K

Actual on primary and secondary mirrors was approx. 7.5 Hrs and approx. 260 L of LHe indicating that the thermal joints were poor and controlling the cooldown.

Estimate of Contact Conductance Across Thermal Joints for SIRTF

The following page presents a figure from a report on Thermal Conductance across Bolted Joints presented by Jerry Siebert at the 10th International Cryogenic Engineering Conference. The data was interpreted for the cooldown ranges of interest for SIRTF and the following coefficients derived:

600 mW/K @ 2K
3000 mW/K @ 2-20K
12000 mW/K @ 20K and above


CONTACT FORCE: 18000N (4000 LBS)
CONTACT AREA: 2.3 CM²
INDIUM
BARE
GOLD
GOLD-COATED ALUMINUM
K_G (6061-T6)
K_G (5083-0)
THERMAL CONTACT CONDUCTANCE, WK^{-1}
TEMPERATURE, K
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
1
2
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5
6
7
8
9
10

A/N 4554

Cooldown Limiting Factors

The controlling factor that limits the flow rate of SfHe during cooldown of the receiver (SIRTF flight dewar) and SIRTF telescope and MIC is the ability to vent the vapor formed when the liquid is boiled. Calculations made with the supply pressure near 1 atmosphere indicates 200L/h of liquid He is feasible even at 300K line temperature. However, at 4psia this flow is not possible for line temperatures above 75K. The end of the vent line (where the flow limit is established) will not be this cold. At this time, the optimum SfHe flow rate time-line profile has not been established. If 200L/h of flow should be required through a warm vent line, the line size needs to be larger (approx. double the area). It is likely that this large flow rate is not needed (nor desired) during the early stages of cooldown with the heat exchanger loop on the main tank.

The curves show the limiting flow in the vent line. The data is the same but expressed as mass per time (lbm/s) and equivalent volume per time of SfHe (L/h). They are valid for cooldown venting and for liquid filling venting.

The calculations were made for constant temperature of the gas along the length of the line. This requires a small heat flow into the gas from the pipe. A check was made for some values with no heat flow to the gas (adiabatic flow) and the results are within 10% of the isothermal values plotted. The thermophysical properties were obtained from the NBS TN 622 tables for He.

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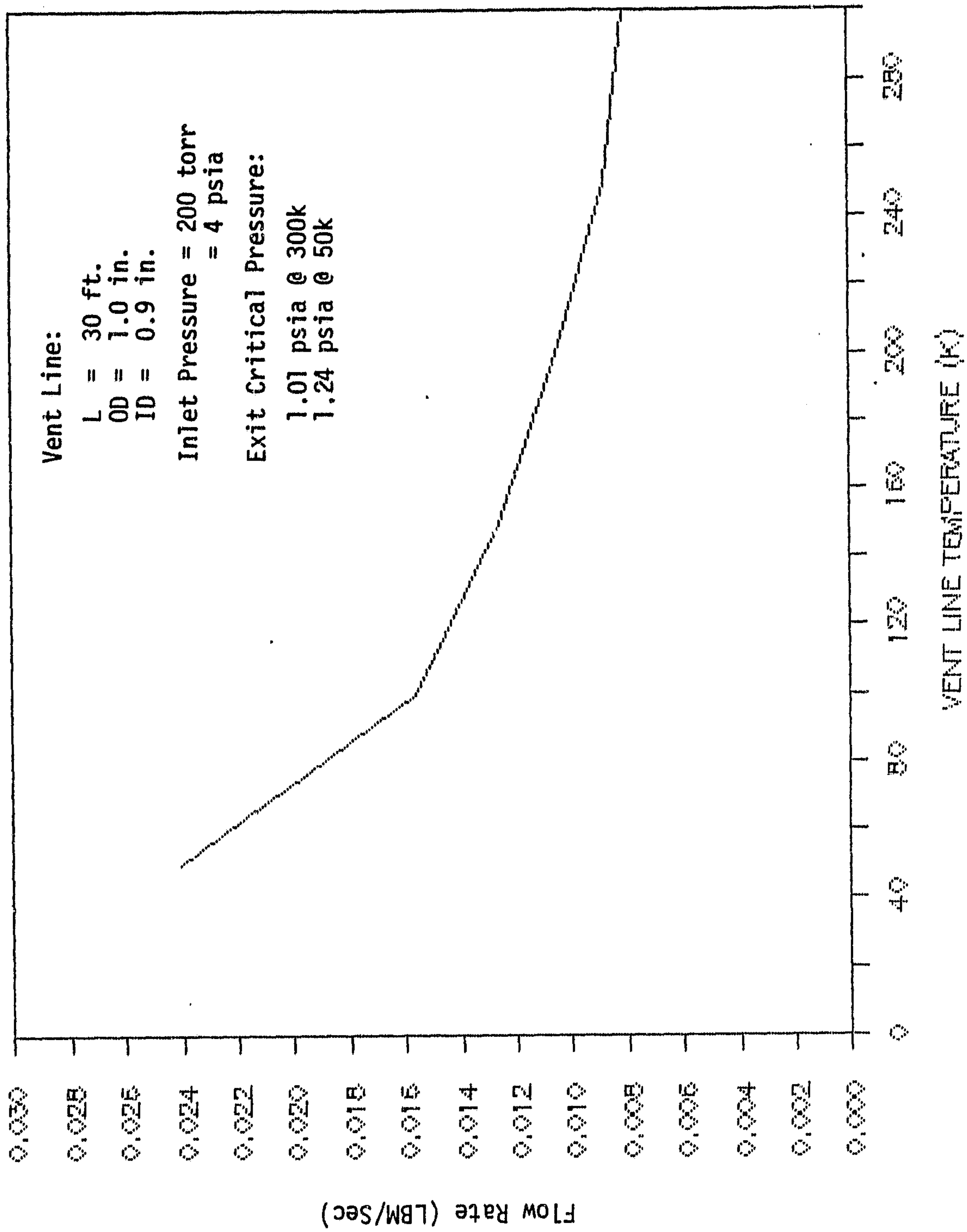
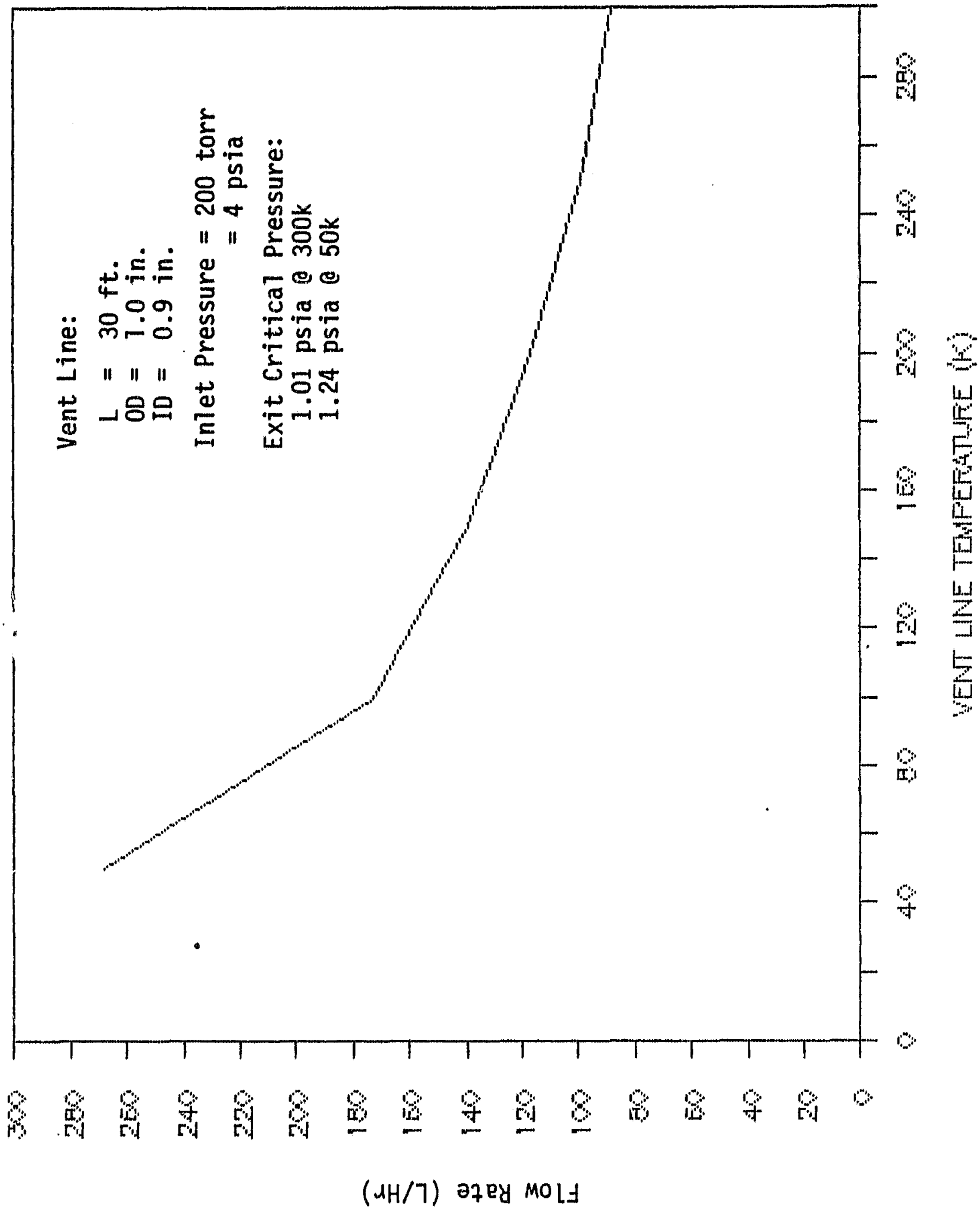


Flow Rate with Limiting Gas Flow



Flow Rate with Critical Flow

Heat Transfer Coefficient and Resulting Conductance in Single Tube Heat Exchanger Loop for SIRTF Cooldown

The heat transfer coefficient between the GHe and the interior of the main tank of SIRTF is expected to be very small during cooldown before LHe is accumulated in the tank. A "stagnant" gas film is expected with the conductance equivalent to only gas conduction. A system is proposed with a tube welded to the main tank at the interface to the telescope mount and MIC mount that makes only one turn around the inner perimeter of the tank. The heat transfer coefficient then becomes forced convection in zero-gravity and the equivalent conductance is much higher. When the tube nears the boiling temperature of the entering SfHe, the boiling two-phase heat transfer coefficient becomes very high even in zero-gravity if a twisted ribbon is inserted inside the 0.9 in tube to give a swirling motion that will throw the liquid to the tube wall and displace the vapor film.

In order to evaluate the concept, values of the heat transfer coefficient, h, have been calculated for the condition of gas flow above the He boiling point. Forced convection correlation is the accepted one for this case and is

$$Nu = 0.23\ Re^{0.8}\ Pr^{1/3}$$

The heat transfer coefficient, h, is in the Nusselt number, Nu, and the equivalent conductance then becomes (hA_s) where A_s is the inner surface area of the tube that forms the heat exchanger.

The resulting conductance is plotted in the figure for various average GHe temperatures and are organized in the form for direct inclusion in the SIRTF SINDA thermal model. In order to properly evaluate the system that includes the heat exchanger loop and the gas conduction to the tank, the preliminary thermal model should be expanded with a few additional nodes. The conductance values for the gas conduction and for the forced convection heat exchanger loop are based on the GHe temperature and not the exit temperature. The heat conductance in the heat transfer loop is added to the gas conduction value for direct injection of He into the tank. A replacement of conductances in the present model will not predict the full potential value of

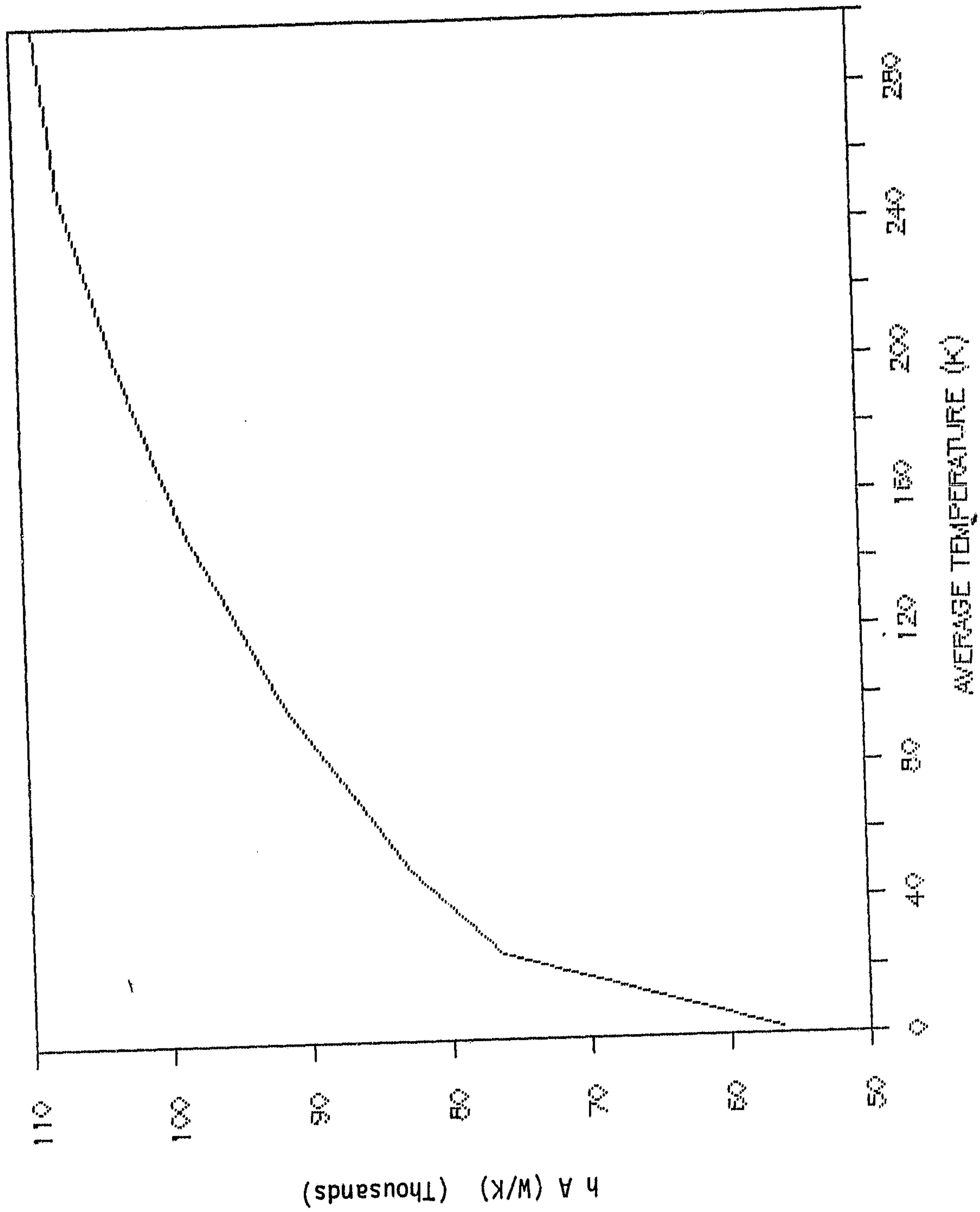
the new system concept. Also care in coupling the concentrated thermal capacitance nodes of the main tank, MIC and telescope needs to be used to take advantage of the improved thermal network possible with the heat exchanger loop addition.

The values for the curve were calculated for a mass flow rate equivalent to a constant LHe flow of 200L/h. As shown in SER DER-001, the vent line from the main tank will not permit this mass flow at warm temperatures. At the present we have not attempted to use the SfHe in an optimum flow time-line profile to minimize the time for cooldown and fill and the amount of He carried into orbit.

There are some important considerations with respect to the flow rate during cooldown. It is important to keep the total cooldown and fill time short so that it will not impact the length of the shuttle mission. Also, it is important to use the SfHe carried into orbit efficiently to eliminate waste and the size and weight carried up. Helium has a high sensible heat capacity relative to its latent heat capacity. If the GHe is dumped overboard when cold, the sensible heat capacity (refrigeration) is not realized and therefore wasted. If the flow rate is high during the initial stages of cooldown the heat transfer rate can be unnecessarily high and the resulting exiting temperature unnecessarily low. This results in a low overall heat exchange efficiency which is not offset by a corresponding shortened mission time. Refrigeration is wasted. The heat transfer rate tends to be naturally high at the warm temperatures existing during early cooldown. The limiting flow rate tends to be naturally small at the same time.

Therefore, we need to take advantage of these features and optimize the system parameters to optimize the natural characteristics available.

It would seem that a moderate flow rate at the beginning of cooldown, increasing as the components become colder, and followed by a high flow rate when liquid He is retained in the SIRTF tank tends to fit the natural way the cooldown and fill can be implemented with proper design.

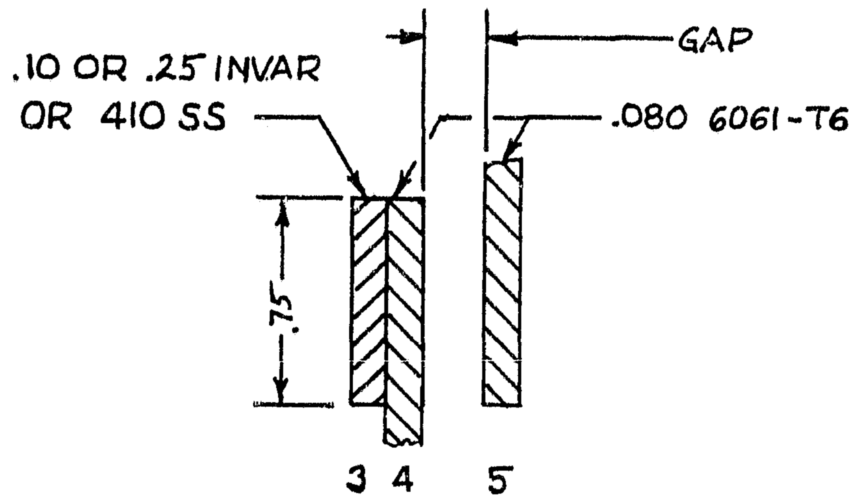


Gaseous Helium Conductance with Heat Exchanger

APPENDIX E

MECHANICAL ANALYSIS OF SHRINK FIT SHIELDS

For preliminary study, ignore the effect of aluminum shields "bottle-necking."



Solved as a 3-ring problem using BERT, (a thermal ring program written by R. Taylor) and assuming a negative interference between rings 4 and 5 (a gap) as an initial condition.

P45 summarized in the following tables is the final pressure between rings 4 and 5, or the shield and the cap. F_3 is the stress in the Invar or 410 SS ring and f_4 is the stress in the aluminum cap. Shield 1 is the OVCS, shield 2 is the MVCS, shield 3 is the IVCS, and shield 4 is the inner shield attached to the cryogen tank.

Shield 1

T_{BASE} = 300°K
T_{FINAL} = 200°K

R_4 = 36.85 t = 0.1, 36.70, t = 0.25
R_5 = 36.95
R_6 = 37.03
R_9 = 37.11

INVAR	W_3 = 0.75	α_3 = 3.-7	E_3 = 2.1 + 7
Al	W_4 = 0.75	α_4 = 2.-5	E_4 = 1. + 7
Al	W_5 = 0.75	α_5 = 2.-5	E_5 = 1. + 7
410 SS	W_3 = 0.75	α_3 = 9.-6	E_3 = 3. + 7

INVAR t_3 = 0.10

Gap (in.)	P_{34} (psi)	P_{45} (psi)	Invar f_3 (psi)	Al f_4 (psi)	f_5 (psi)
0.00	48	24	17,712	11,097	11,121
0.01	45	20	16,605	11,559	9,268
0.02	41	15	15,129	12,022	6,951
0.04	35	5	12,915	13,871	2,317
0.06	28	-3	No Contact		
0.08					
0.10					

INVAR $t_3 = 0.25$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3	f_4	f_5
0.00	65	32	9,594	15,258	14,828
0.01	61	28	9,004	15,258	12,975
0.02	56	23	8,266	15,258	10,658
0.04	48	12	7,085	16,646	5,561
0.06	39	1	5,756	17,570	463
0.08	29	-8	No Contact		
0.10					

Shield 2

$T_{BASE} = 300$
$T_{FINAL} = 118$

$R_4 = 35.24$ ($t = 0.10$) 35.39 $t = 0.25$
$R_5 = 35.34$
$R_6 = 35.42$
$R_7 = 35.50$

INVAR	$W_3 = 0.75$	$\alpha_3 = 1.2^{-6}$	$E_3 = 2.1^{+7}$
Al	$W_4 = 0.75$	$\alpha_4 = 1.9^{-5}$	$E_4 = 1.^{+7}$
Al	$W_5 = 0.75$	$\alpha_5 = 1.9^{-5}$	$E_5 = 1.^{+7}$
410 SS	$W_3 = 0.75$	$\alpha_3 = 8.1^{-6}$	$E_3 = 3.^{+7}$

INVAR $t_3 = 0.10$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3 (psi)	f_4 (psi)	f_5 (psi)
0.00	83	41	29,299	18,575	18,173
0.01	80	36	28,240	19,459	15,957
0.02	76	32	26,828	19,459	14,184
0.04	68	21	24,004	20,786	9,308
0.06	61	12	21,533	21,670	5,319
0.08	55	1	19,415	23,882	443
0.10	47	-8	No Contact		

INVAR $t_3 = 0.25$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	Invar f_3 (psi)	Al f_4 (psi)	Al f_5 (psi)
0.00	112	56	15,680	24,822	24,822
0.01	108	51	15,120	25,265	22,606
0.02	103	45	14,420	25,709	19,946
0.04	92	33	12,880	26,152	14,627
0.06	83	23	11,620	26,595	10,195
0.08	73	11	10,220	31,914	4,876
0.10	63	0	No Contact		

410 SS $t_3 = 0.10$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	410 SS f_3 (psi)	Al f_4 (psi)	Al f_5 (psi)
0.00	57	29	19,950	12,411	12,854
0.01	53	24	18,550	12,854	10,638
0.02	49	19	17,150	13,298	8,422
0.04	41	8	14,350	14,627	3,546
0.06	33	-3	No Contact		

410 SS $t_3 = 0.25$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	410 SS f_3 (psi)	Al f_4 (psi)	Al f_5 (psi)
0.00	73	36	10,220	16,400	15,957
0.01	68	31	9,520	16,400	13,741
0.02	63	25	8,820	16,844	11,081
0.04	52	13	7,280	17,287	5,762
0.06	41	1.3	5,740	17,597	576
0.08	31	-11	No Contact		

Shield 3

T_{BASE} = 300°K
T_{FINAL} = 52°K

R_4 = 34.02, t = 0.1, 33.87, t = 0.25
R_5 = 34.12
R_6 = 34.20
R_9 = 34.28

INVAR	$W_3 = 0.75$	$a_3 = 1.7^{-6}$	$E_3 = 2.1^{+7}$
Al	$W_4 = 0.75$	$a_4 = 1.6^{-5}$	$E_4 = 1.^{+7}$
Al	$W_5 = 0.75$	$a_5 = 1.6^{-5}$	$E_5 = 1.^{+7}$
410 SS	$W_3 = 0.75$	$a_3 = 6.8^{-6}$	$E_3 = 3.^{+7}$
INVAR	$t_3 = 0.10$		

Gap (in.)	P_{34} (psi)	P_{45} (psi)	Invar f_3 (psi)	Al f_4 (psi)	f_5 (psi)
0.00	95	47	32,395	20,496	20,116
0.01	91	41	31,031	21,350	17,548
0.02	87	36	29,667	21,777	15,408
0.04	79	25	26,939	23,058	10,700
0.06	71	15	24,211	23,912	6,420
0.08	63	4	21,483	25,193	1,712
0.10	56	-7	No Contact		

INVAR t_3 - 0.25

Gap (in.)	P_{34} (psi)	P_{45} (psi)	Invar f_3 (psi)	Al f_4 (psi)	f_5 (psi)
0.00	127	64	17,269	26,903	27,392
0.01	123	57	16,726	28,182	24,396
0.02	117	52	15,910	27,755	22,256
0.04	107	39	14,550	29,036	16,692
0.06	96	27	13,054	29,463	11,556
0.08	85	15	11,558	29,890	6,420
0.10	75	3			

410 SS t_3 = 0.10

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3 (psi)	f_4 (psi)	f_5 (psi)
0.00	69	35	23,529	14,518	14,980
0.01	65	29	22,165	15,372	12,412
0.02	61	24	20,801	15,799	10,272
0.04	52	12	17,732	17,080	5,136
0.06	43	1	14,663	17,934	428
0.08	33	-11	No Contact		
0.10					

410 SS $t_3 = 0.25$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	Invar f_3 (psi)	Al f_4 (psi)	f_5 (psi)
0.00	88	44	11,966	18,788	18,832
0.01	83	37	11,286	19,642	15,836
0.02	77	32	10,470	19,215	13,696
0.04	65	19	8,839	19,642	8,132
0.06	55	7	7,479	20,496	2,996
0.08	43	-7	No Contact		

Shield 4

$T_{BASE} = 300°K$

$T_{FINAL} = 2°K$

$R_4 = 33.38$ (t = 0.10, 33.23, t = 0.25

$R_5 = 33.48$

$R_6 = 33.56$

$R_9 = 33.64$

INVAR	$W_3 = 0.75$	$\alpha_3 = 1.8^{-6}$	$E_3 = 2.1^{+7}$
Al	$W_4 = 0.75$	$\alpha_4 = 1.4^{-5}$	$E_4 = 1.^{+7}$
Al	$W_5 = 0.75$	$\alpha_5 = 1.4^{-5}$	$E_5 = 1.^{+7}$
410 SS	$W_3 = 0.75$	$\alpha_3 = 5.9^{-6}$	$E_3 = 3.^{+7}$

INVAR $t_3 = 0.10$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3 (psi)	f_4 (psi)	f_5 (psi)
0.00	99	49	32,967	20,950	20,580
0.01	95	44	31,635	21,369	18,480
0.02	91	37	30,303	22,626	15,540
0.04	83	27	27,639	23,464	11,340
0.06	75	16	24,975	24,721	6,720
0.08	67	4	22,311	26,397	1,680
0.10	59	-7	No Contact		

INVAR $t_3 = 0.25$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3 (psi)	f_4 (psi)	f_5 (psi)
0.00	133	67	17,745	27,654	28,140
0.01	128	60	17,078	28,492	25,200
0.02	123	53	16,411	29,330	22,260
0.04	111	41	14,810	29,330	17,220
0.06	100	28	13,342	30,168	11,760
0.08	89	16	11,874	30,587	6,720
0.10	49	4	10,540	31,425	1,680

Shield 4B

410 SS $t_3 = 0.10$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3 (psi)	f_4 (psi)	f_5 (psi)
0.00	75	37	24,975	15,992	15,540
0.01	71	32	23,643	16,341	13,440
0.02	65	25	21,645	16,760	10,500
0.04	56	13	18,648	18,017	5,460
0.06	47	3	15,651	18,436	1,260
0.08	57	-9	No Contact		

Shield 4BB

410 SS $t_3 = 0.25$

Gap (in.)	P_{34} (psi)	P_{45} (psi)	f_3 (psi)	f_4 (psi)	f_5 (psi)
0.00	95	47	12,675	20,112	19,740
0.01	89	41	11,874	20,112	17,220
0.02	83	35	11,074	20,112	14,700
0.04	72	21	9,606	21,369	8,820
0.06	60	8	8,005	21,788	3,360
0.08	48	-4	No Contact		

APPENDIX F
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APPENDIX G
GLOSSARY OF ACRONYMS AND SYMBOLS

Acronyms

ARC	Ames Research Center
ASE	Airborne Support Equipment
BASD	Ball Aerospace Systems Division
BPS	Bits Per Second
COBE	Cosmic Background Explorer
CFMF	Cryogenic Fluids Management Facility
EMU	Extra Vehicular Mobility Unit
EV	Extra Vehicular
EVA	Extra Vehicular Activity
GHe	Gaseous Helium
GSFC	Goddard Spaceflight Center
IRAS	Infrared Astronomical Satellite
IVA	Intravehicular Activity
IVCS	Inner Vapor Cooled Shields
J-T	Joule-Thompson
JSC	Lyndon B. Johnson Space Center
KSC	Kennedy Spaceflight Center
LeRC	Lewis Research Center
LHe	Liquid Helium
LOX	Liquid Oxygen
LNZ	Liquid Nitrogen
MFR	Manipulator Foot Restraint
MIC	Multiple Instrument Cavity
MMS	Multimission Modular Spacecraft
MMV	Manned Maneuvering Unit
MRMS	Mobile Remote Manipulator System
MVCS	Middle Vapor Cooled Shields
NASA	National Aeronautics and Space Administration
NHB	NASA Handbook

OMS	Orbital Maneuvering Systems
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replaceable Unit
ORV	Orbital Recovery Vehicle
OVCS	Outer Vapor Cooled Shields
RCS	Reaction Control Subsystem
RMS	Remote Manipulator System
SfHe	Super Fluid Helium
SIRTF	Space Infrared Telescope Facility
STS	Space Transportation System

Symbols

cm	Centimeter (10^{-2} m)
hr	Hour
in	Inch
K	Kelvin
kg	Killogram
km	Killometer (10^{3}m)
lb.	Pound
l	Liter
L	Latent Heat of Vaporization
m	Meter or Mass
mW	Milliwatt (10^{-3}W)
P	Power or Pressure
psi	Pound per Square Inch
Q	Power
S	Entropy
sec	Second
T	Temperature
W	Watt
α	Absorbtivity
ϵ	Emissivity
μm	Micrometer (10^{-6}m)
ρ	Density

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16. Abstract

The Space Infrared Telescope Facility (SIRTF) is a long-life cryogenically cooled space-based telescope for infrared astronomy from 2 um to 700 um currently under study by NASA-ARC (Reference AP), and planned for launch in approximately the mid 90's.

SIRTF will operate as a multi-user facility, initially carrying 3 instruments at the focal plane. It will be cooled to below 2K by superfluid liquid helium to achieve radiometric sensitivity limited only by the statistical fluctuations in the natural infrared background radiation over most of its spectral range. The lifetime of the mission will be limited by the lifetime of the liquid helium supply, and is currently baselined to be 2 years.

This study investigated the telescope changes required to allow in-space replenishment of the 2,000 liter superfluid helium tank. A preliminary design for the space services equipment was also developed. The impacts of basing the equipment and servicing on the space station were investigated. Space replenishment and changeout of instruments required changes to the telescope design and preliminary concepts are presented.

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